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THE MINERAL QUALITY PROBLEM IN THE COLORADO RIVER BASIN. APPENDIX B. PHYSICAL AND ECONOMIC IMPACTS

Environmental Protection Agency
Denver, Colorado

1971

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THE MINERAL QUALITY PROBLEM
IN THE COLORADO RIVER BASIN

APPENDIX B

PHYSICAL AND ECONOMIC IMPACTS

UNITED STATES
ENVIRONMENTAL PROTECTION AGENCY
REGIONS VIII AND IX

1971

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THE ENVIRONMENTAL PROTECTION AGENCY

The Environmental Protection Agency was established by Reorganization Plan No. 3 of 1970 and became operative on December 2, 1970. The EPA consolidates in one agency Federal control programs involving air and water pollution, solid waste management, pesticides, radiation and noise. This report was prepared over a period of eight years by water program components of EPA and their predecessor agencies--the Federal Water Quality Administration, U.S. Department of Interior, April 1970 to December 1970; the Federal Water Pollution Control Administration, U.S. Department of Interior, October 1965 to April 1970; the Division of Water Supply and Pollution Control, U.S. Public Health Service, prior to October 1965. Throughout the report one or more of these agencies will be mentioned and should be considered as part of a single agency--in evolution.

PREFACE

The Colorado River Basin Water Quality Control Project was established as a result of recommendations made at the first session of a joint Federal-State "Conference in the Matter of Pollution of the Interstate Waters of the Colorado River and its Tributaries," held in January of 1960 under the authority of Section 8 of the Federal Water Pollution Control Act (33 U.S.C. 466 *et seq.*). This conference was called at the request of the states of Arizona, California, Colorado, Nevada, New Mexico, and Utah to consider all types of water pollution in the Colorado River Basin. The Project serves as the technical arm of the conference and provides the conferees with detailed information on water uses, the nature and extent of pollution problems and their effects on water users, and recommended measures for control of pollution in the Colorado River Basin.

The Project has carried out extensive field investigations along with detailed engineering and economic studies to accomplish the following objectives:

(1) To determine the location, magnutide, and causes of interstate pollution of the Colorado River and its tributaries.

(2) To determine and evaluate the nature and magnitude of the damages to water users caused by various types of pollution.

(3) To develop, evaluate, and recommend measures and programs for controlling or minimizing interstate water pollution problems.

In 1963, based upon recommendations of the conferees, the Project began detailed studies of the mineral quality problem in the Colorado River Basin. Mineral quality, commonly known as salinity, is a complex Basin-wide problem that is becoming increasingly important to users of Colorado River water. Due to the nature, extent, and impact of the salinity problem, the Project extended certain of its activities over the entire Colorado River Basin and the Southern California water service area.

The more significant findings and data from the Project's salinity studies and related pertinent information are summarized in a report entitled, "The Mineral Quality Problem in the Colorado River Basin." Detailed information pertaining to methodology and findings of the Project's salinity studies is presented in three appendices to that report - Appendix A, "Natural and Man-Made Conditions Affecting Mineral Quality," Appendix B, "Physical and Economic Impacts," and Appendix C, "Salinity Control and Management Aspects."

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CHAPTER I. INTRODUCTION

Salinity is one of the most serious water quality problems in the Colorado River Basin. Like many streams in the arid West, the Colorado River displays a progressive increase in salinity (total dissolved solids)[1] between its headwaters and its mouth. Salinity concentrations in the Lower Colorado River (below Lees Ferry, Arizona) are approaching critical levels for municipal, industrial, and agricultural water use. In the face of this present situation, planned and proposed water resource developments, primarily in the Upper Basin, will cause further increases in salinity concentrations in the Lower Colorado River.

As a part of its overall study of the salinity problem, the Colorado River Basin Water Quality Control Project (Project) carried out detailed studies to evaluate the physical and economic impacts associated with anticipated degradation in the mineral quality of Colorado River water. The methods of investigation and the results of these studies are presented in this appendix.

Before the impacts associated with degradation in mineral quality could be determined, it was necessary to understand the effect of salinity on various beneficial uses of water The general effects of salinity on domestic, industrial, agricultural, and other beneficial uses are discussed in Chapter II of this appendix. Hardness, a water quality parameter closely related to total dissolved solids (TDS), is also discussed since it has significant effects on domestic and industrial water uses.

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[1] The terms "salinity" and "total dissolved solids" are used synonymously throughout this report.

The mineral quality conditions presently prevailing at various locations along the river and the conditions likely to occur in the years 1980 and 2010 are described in Cahpter III In order to determine these conditions, a mathematical flow and salt loading routing model was developed for the Colorado River Basin. Published flow and salinity data supplemented by data collected by the Project were used in this model.

Once the general effects of salinity on beneficial uses of water were identified and the anticipated mineral quality for the river system had been determined, methods were developed to quantify the anticipated quality effects in economic terms. Methods were developed also to determine the direct impact of salinity. The methods and results for the direct penalty-cost evaluation are described in Chapter IV.

The first step in the direct penalty-cost evaluation involved the development of methods for relating increases in TDS to the economic cost which each user would incur. Alternative methods were investigated based on the study of the effects of salinity on beneficial uses of water. After careful analysis, methods were chosen for evaluating the effects on each category of water use. Among factors considered in this analysis were the hydrology of the Basin, the quantities of water used by various users, the economy of the Basin, the population of the Basin, and existing water-treatment technology. The amount and location of direct penalty costs incurred by water users in the Basin were determined by the magnitude of expected salinity increase and the volume of anticipated water use.

In addition to the direct impact of degradation in mineral quality upon water users, there are indirect economic effects upon the regional economy. These indirect effects result from the close interdependence of one industry to another, which causes direct effects on one industry to produce indirect effects on another. The first step in evaluating this impact was to investigate the structure of the economy. An input-output, or transactions, table was constructed to identify the flow of goods and services between groups of industries or sectors. Once constructed, the transactions table became a series of linear simultaneous equations that could be solved with a high-speed digital computer utilizing methods of matrix algebra. Direct changes in the economic structure caused by salinity were thereby translated into indirect, or "multiplier," effects to arrive at the total regional economic impact associated with mineral quality degradation. A final step of the analysis was to determine the sensitivity of the calculations to some of the underlying assumptions which were made. A more detailed discussion of the methods used in calculating the total regional economic impact and the results obtained are presented in Chapter V.

CHAPTER II. EFFECTS OF SALINITY ON BENEFICIAL USES OF WATER

Water polluting substances have been traditionally classified in relation to their degradability, principally by biological and bacteriological processes. Biochemical oxygen demand, coliform density, organic content, and nutrient concentrations are classic pollutant properties that are degradable and subject to natural or man-induced biological treatment. Some pollutants such as synthetic detergents, certain classes of pesticides, or other organic substances are only slightly degradable. A large class of substances, primarily the inorganic or complex organic chemicals, exists that is non-degradable or conservative. Since inorganic chemicals are not degraded by the usual stream purification processes, the concentrations typically increase with each water use as the material moves downstream. In the Colorado River Basin the mineral constituents of total dissolved solids are of prime importance in the class of non-degradable or conservative substances.

The effect of polluting substances is generally discussed in terms of their impact upon water uses. In the case of salinity two general categories of water uses should be distinguished: consumptive and non-consumptive. The former includes agricultural uses, such as irrigation and livestock watering, as well as municipal and industrial uses. The latter comprises such uses as hydroelectric power generation, navigation, water-oriented recreation, fish and wildlife habitat, ground water recharge, silt control, and general water quality control. The division obviously arises from the fact that consumptive uses remove water from the system, whereas the non-consumptive uses utilize water *in situ*. In the following two sections the affected uses in these two categories are discussed in detail.

CONSUMPTIVE USES

Municipal

The use of water for domestic purposes is generally considered to be the highest beneficial use. Standards for drinking water utilized by carriers subject to the Federal Quarantine Regulations have been established and revised by the United States Public Health Service since 1914, the latest being issued in 1962.(1) These standards have been adopted by most states for all public water supplies.

Included in these standards are limits for certain inorganic materials which are mandatory in some cases and recommended in other cases. The level of total hardness in a water supply is of primary interest in assessing water quality effects on domestic use. A single criterion for maximum hardness is not recommended for public supplies by the U. S. Public Health Service since public acceptance varies from community to community and is related to the normal levels for a particular community. However, other publications do contain numerous recommendations for desirable levels of hardness in public water supplies. A number of these recommendations are summarized in "Water Quality Criteria."(2) Also, according to Sawyer(3) waters are normally classified in terms of degree of hardness as follows:

0 - 75 mg/1	Soft
75 - 150 mg/1	Moderately Hard
150 - 300 mg/1	Hard
300 Up	Very Hard

Using these criteria, all raw water supplies derived from the Colorado River at or below Lake Mead would be classified as "very hard."

Also of interest in domestic water supplies are the levels of total dissolved solids. The Public Health Service(1) recommends a limit of 500 mg/l provided that more suitable supplies are not or cannot be made available. A previous issuance of the Drinking Water Standards had permitted a TDS concentration of 1,000 mg/l in the absence of an alternate source, but this provision is not included in the present Public Health Service standards. Increases in the concentration of hardness and salinity can cause damages to municipal water users in five ways discussed in the following sections.

Potable Water Supply. In extreme cases mineralization may render a public water supply unfit or highly undesirable for human consumption. One example of this situation within the Colorado River Basin is the experience at Yuma, Arizona. The penalty costs in this situation could include: (1) the cost of obtaining water rights and developing a new water supply, (2) losses associated with abandoning the existing supply and appanages, and (3) differences in operation and maintenance costs between the old and new water supply facilities.

Water Softening. In communities where water softening is practiced, either by municipal softening or invidivual home water softeners, harder water increases the cost of treatment. Resulting increments of treatment costs can be related to anticipated increases in the hardness of the water supply.

Soap and Detergent Consumption. Communities that have hard water supplies and do not elect to provide softening nevertheless incur penalty costs in the form of higher expenditures for soap, synthetic detergents, and softening additives. Such costs are normally greater than would be incurred in a central softening treatment plant. In areas where portions of the population receive softened water and others do not, penalty costs incurred from hardness are the sum of two items: (1) the operation and maintenance of softening equipment for the portion of the population that benefits by such treatment, and (2) the additional cost of soap and detergents incurred by the remainder of the community.

Corrosion and Scaling of Metal Water Pipes and Fittings. The corrosiveness of water is governed by many factors such as temperature; presence of dissolved gasses, acids, and mineral salts; and electrochemical properties of the materials utilized. No simple relationship exists between the levels of mineral salts present and corrosiveness. Therefore, translation of such a relationship into tangible economic penalty costs is difficult and was not utilized in this study. Scaling, as evidenced in home hot-water systems such as water heaters, is also difficult to assess in terms of monetary values.

Accelerated Fabric Wear. Laundering with hard water has been stated to be a factor in the hastening of wear of clothing and other textile products. One reference(4) cites a 25-percent faster rate of wear with hard water than with soft. However, the relationship of fractional changes in hardness to fabric wear is difficult to quantify and, for this reason, penalty costs were not assessed for this factor.

Industrial

The effect of water quality on industrial uses is difficult to generalize because of the varied purposes to which industry puts water. A supply that meets Drinking Water Standards is often acceptable, but some industries require even better quality water. For example, the confectionery trade and certain paper-making and textile processes require water containing not over 200 parts per million (ppm) of dissolved solids and an iron content of 0.1 - 1.0 ppm. This is considerably better than domestic quality water.

Industrial water use may be classified by purpose as cooling, boiler feed, process, or general purpose. Data in a 1964 publication by the State of California Department of Water Resources(5) indicate that the relative magnitudes of these uses in California were: (1) cooling - 57 percent, (2) boiler feed - nine percent, (3) process - 25 percent, and (4) general purpose - nine percent. These relative percentages apply to the State of California as a whole and do not reflect the effects of recirculation of water which is quite significant in that state, especially for cooling and boiler feed operations.

When the raw water supply does not meet quality criteria for the various purposes described above, industry uses two general types of treatment approaches: external treatment or internal treatment. External treatment is used when better quality water is required for nearly every purpose for which water is to be used. Such methods include water softening, evaporation, and demineralization. Internal treatment, on the other hand, is used to improve quality for a particular purpose such as process water. This type of treatment includes such operations as chromate addition and chlorination in cooling systems for control of corrosion and slime. In some cases, economic considerations lead to a combination of the two treatment approaches.

Fundamental processes, water quality criteria, treatment methods, and associated penalty cost considerations for the four major industrial water uses are summarized in the following section.

Boiler Feed Water. Quality of boiler feed water is a significant factor in the (1) rate of scale formation on heating surfaces, (2) degree of corrosion to the system, and (3) quality of produced steam. Three quality parameters - total dissolved solids, alkalinity, and hardness - are most important, their relative significance being dependent upon the system's operating temperature and pressure.

For convenience and uniformity, the operating temperatures of systems are translated into equivalent pressures. Recommendations for quality requirements vary widely; one such recommendation is that of the American Boiler and Affiliated Industries shown in Table 1.

Table 1. American Boiler and Affiliated Industries' Limits for Boiler Water Quality Concentrations in Units with a Steam Drum[a]

Pressure at Outlet of Steam Generating Unit (lbs. per sq. in.)	Total Solids (ppm)	Total Alkalinity (ppm)	Suspended Solids (ppm)
0 - 300	3500	700	300
301 - 450	3000	600	250
451 - 600	2500	500	150
601 - 750	2000	400	100
751 - 900	1500	300	60
901 - 1000	1250	250	40
1001 - 1500	1000	200	20
1501 - 2000	750	150	10
2001 and higher	500	100	5

---

[a] Nordel, Eskel, "Water Treatment for Industrial and Other Uses," Second Edition, Reinhold Publishing Corporation, New York, 1961, p. 273. (Reference No. 6)

Another recommendation for boiler feed water quality requirements was formulated by the Committee on Water Quality Tolerances for Industrial Uses, NEWWA as shown in Table 2.

Table 2. Suggested Limits of Tolerance for Boiler Feed Waters

(From Progress Report of the Committee on Water Quality Tolerances for Industrial Uses, NEWWA) (1959)

(units are in mg/l except as otherwise noted)

Pressure (psi)	0-150	150-250	250-400	Over 400
Turbidity	20	10	5	1
Color	80	40	5	2
Oxygen consumed	15	10	4	3
Dissolved oxygen**	2.0[a]	0.2[a]	0.0	0.0
Hydrogen sulfide*	5	3	0	0
Total hardness ($CaCO_3$)	80	40	10	2
Sulfate-carbonate ratio (ASME) ($Na_2SO_4:Na_2CO_3$)	1:1	2:1	3:1	3:1
Aluminum oxide	5	0.5	0.05	0.01
Silica	40	20	5	1
Bicarbonate**	50	30	5	0
Carbonate	200	100	40	20
Hydroxide	50	40	30	15
Total solids[b]	3000-500	2500-500	1500-100	50
pH value (Min.)	8.0	8.4	9.0	9.6

* Except when odor in live steam would be objectionable.

**Limits applicable only to feed water entering boiler, not to original water supply.

[a] Given as ml per liter. Multiply by 0.70 for ppm.

[b] Depends on design of boiler.

For the Project's analysis an operating tolerance of 3,500 mg/l was selected because: (1) most boilers in the Colorado River Basin appear to be operated in the lower pressure ranges, (2) the American Boiler Manufacturer's Association stipulates a limit of 3,500 mg/l for boilers operating at 300 psi or less in its standard guarantee of steam purity[1], and (3) the relatively high tolerance provided a somewhat conservative estimate of boiler feed water penalties.

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[1] Betz Handbook of Industrial Water Conditioning, Betz Laboratories, Inc., Philadelphia, 1962, p. 211. (Reference No. 7)

For highly mineralized water supplies, some form of softening is mandatory before use as a boiler feed water. While the costs of water softening are generally proportional to the amount of hardness removed, the cost of evaporation to produce distilled water is essentially independent of the level of mineral constituents in the raw water supply. For units operating at pressure levels where boiler feed water softening by more conventional means is appropriate, the penalty costs due to salinity increases can be partially assessed in terms of increased treatment costs. Such an approach is less readily applicable to high-pressure boilers since the cost of obtaining the necessary quality by distillation or evaporation has little or no dependence on influent quality. Raw water quality may, however, affect the cost of pre-treatment before evaporation.

In order to maintain a level of total dissolved solids in the boiler system that can be tolerated, some of the concentrated boiler water must be removed from the system. This process of solids removal by either continually or intermittently drawing off a portion of the circulating water is known as "blowdown." The quality of the boiler feed water introduced to the system in relation to the concentration that can be tolerated within the system determines the amount of blowdown required.

Cooling Water. Cooling water is used for a variety of purposes, including the cooling of condensers, internal combustion engines, and compressors. Also included would be water used in air conditioners as well as a variety of other cooling processes.

Although the intake water quality requirements and the extent of water treatment depend in large measure on the particular system employed, there are some generally desirable characteristics of an intake water. The following characteristics are of great significance: low, relatively constant temperature; non-corrosiveness; non-slime forming; non-scaling. The following specific limits on the concentration of quality parameters are presented in the manual, "Water Quality and Treatment."(8)

Turbidity	50 mg/l
Hardness	50 mg/l
Iron	0.5 mg/l
Manganese	0.5 mg/l
Iron and Manganese	0.5 mg/l

Information on industrial cooling water practice available to the Project indicates that, within the Lower Colorado and Southern California areas, the concentration of total dissolved solids in cooling water systems is normally held at a level of 2,000 mg/l. In addition, the publication, "Water Quality Criteria,"(2) states:

> "Among the constituents of natural water that may prove detrimental to its use for cooling purposes are hardness, suspended solids, dissolved gasses, acids, oil, and other organic compounds and slime-forming organisms."

Although cooling water systems are subject to the same type of problems that affect boiler water systems (e.g., scale formation and corrosion), each type of system experiences those problems to a different degree. Once-through systems have fewer scale-buildup problems than either open-recirculating or closed-recirculating systems. A closed system utilizes a heat-exchanging mechanism rather than an evaporative device such as a cooling tower to remove excess heat in the system. Corrosion problems in open-recirculating systems are particularly acute due to the continuous saturation of circulating water with oxygen upon passage through the cooling tower.

Penalty costs for quality degradation are incurred in additional treatment costs and greater makeup water requirements. Calcium carbonate scaling is often controlled by anti-nucleating agents which increase the solubility of calcium carbonate. The use of such agents is limited insofar as it is necessary to limit the mineral concentration by means of blowdown. Often the relative costs of makeup water and treatment methods dictate the magnitude of blowdown. Corrosion prevention is frequently accomplished by corrosion inhibitors like polyphosphates.

Process Water. Process water is used in preparation of the products of industry. This water is either incorporated directly in the finished product, such as in bottled beverages and canned foods, or used in transporting, washing, mixing, dissolving, concentrating, or cooking operations. As might be expected, the water quality requirements vary widely according to type of use and, in some instances as previously noted, they are more exacting than for domestic water supply. In such cases the expense of treating a public water supply to conform to particular industrial needs is accepted as a normal business expense. In view of the great variety of special qualities needed in industrial process waters, it is not feasible to make a comprehensive penalty cost analysis. However, a summary of the water quality tolerance for industrial process water uses is shown in Table 3.

General Purpose Water. General purpose water is used by industry for plant personnel needs (drinking water, sanitation), general cleaning, lawn sprinkling, and fire protection. While drinking water can be

Table 3. Water Quality Tolerance for Industrial Process Uses[a]
(Allowable limits in parts per million)

Industry or Use	Turbidity	Color	Hardness as $CaCO_3$	Iron[b] as Fe	Manganese as Mn	Total Solids	Alkalinity as $CaCO_3$	Odor Taste	Hydrogen Sulfide	Other Requirements[c]
Baking	10	10		0.2	0.2			Low	0.2	P.
Brewing										
Light Beer	10			0.1	0.1	500	75	Low	0.2	P. NaCl less than 275 ppm (pH 6.5 - 7.0)
Dark Beer	10			0.1	0.1	1,000	150	Low	0.2	P. NaCl less than 275 ppm (pH 7.0 or more)
Canning										
Legumes	10		25-72	0.2	0.2			Low	1	P.
General	10			0.2	0.2			Low	1	P.
Carbonated Beverages	2	10	250	0.2	0.2	850	50-100	Low	0.2	P. Organic color plus oxygen consumed less than 10 ppm
Confectionery				0.2	0.2	100		Low	0.2	P. pH above 7.0 for hard candy
Food: General	10			0.2	0.2			Low		P.
Ice	5	5	50	0.2	0.2			Low		P. SiO_2 less than 10 ppm
Laundering			50	0.2	0.2					
Plastics, clear, uncolored	2	2		0.02	200.0	200				
Paper and Pulp										
Groundwood	50	20	130	1.0	0.5					No grit, corrosiveness
Kraft Pulp	25	15	100	0.2	0.1	300				
Soda and Sulfide	15	10	100	0.1	0.05	200				
High-grade Light Papers	5	5	50	0.1	0.05	200				
Rayon (Vicose)										
Pulp Production	5	5	8	0.05	0.03	100	Total 50; Hydroxide 8			Al_2O_3 less than 8 ppm, SiO_2 less than 25 ppm, Cu less than 5 ppm
Manufacture	0.3		55	0.0	0.0					pH 7.8 to 8.3

Table 3. Contd. Water Quality Tolerance for Industrial Process Uses[a]
(Allowable limits in parts per million)

Industry or Use	Turbidity	Color	Hardness as $CaCO_3$	Iron[b] as Fe	Manganese as Mn	Total Solids	Alkalinity as $CaCO_3$	Odor Taste	Hydrogen Sulfide	Other Requirements[c]
Tanning	20	10-100	50-135	0.2	0.2		Total 135; Hydroxide 8			
Textiles: General	5	20		0.25	0.25					
Dyeing	5	5-20		0.25	0.25	200				Constant composition Residual alumina less than 0.5 ppm
Wool Scouring		70		1.0	1.0					
Cotton Bandage	5	5		0.2	0.2			Low		

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[a] Anonymous, "Progress Report of Committee on Quality Tolerance of Water for Industrial Uses," Journal New England Water Works Association, Volume 54, 1940, p. 271. (Reference No. 9)

[b] Limit given applies to both iron alone and the sum of iron and manganese.

[c] "P" indicates that potable water conforming to U. S. Public Health Service standards is necessary.

impaired or rendered unusable by high salinity concentrations, the quantity involved, in comparison to that used elsewhere in the industrial plant, is so small that any penalty costs associated with salinity increases would not be significant.

Hot wash water, which is used in lavatories and plant laundries, may need to be softened but the same penalty cost considerations apply as for municipal and domestic water previously discussed and the quantity of water involved is comparatively insignificant. Increases in salinity and hardness have little effect on water used for general cleaning, lawn sprinkling, and fire protection.

Irrigation

Several characteristics of water are important in relation to its use as an irrigation supply. These characteristics include: (1) the total concentration of soluble salts, (2) the relative proportion of sodium to other cations, (3) the concentrations of boron or other toxic elements, and (4) under certain conditions, the bicarbonate concentration as related to the concentration of calcium plus magnesium. A discussion of each of these characteristics follows and is based on Handbook 60[10] of the U. S. Department of Agriculture, unless otherwise indicated.

The concentration of soluble salts in irrigation water is expressed either in terms of specific electrical conductance, which is a measure of concentration of ions per unit of water, or in terms of total dissolved solids, in milligrams per liter of water. The main adverse effect of a high salt content in irrigation water is in reducing osmotic action, and thereby reducing the uptake of water by plants. Some other effects involve the direct chemical effects upon metabolic reactions of plants (toxic effects), and the indirect effects of changes in soil structure, permeability, and aeration.(11)

It is difficult to set precise salinity limits for irrigation water for several reasons, including: (1) plants vary widely in their tolerance to salinity and to specific constituents, (2) soil types, climate conditions, and irrigation practices influence the reactions of a crop to salt constituents, and (3) the interrelationships between constituents may be highly significant. Although absolute limits cannot be set for irrigation water, the U. S. Department of Agriculture's Salinity Laboratory has established some general classifications which are shown in Table 4.

Table 4. Classification of Irrigation Water as to Salinity Hazard

Classification	Conductivity micromhos/cm
Low	100 - 250
Medium	250 - 750
High	750 - 2250
Very High	$>$ 2250

Salts dissolved in irrigation water tend to accumulate in the soil on which they are applied. This accumulation eventually causes the soil to become too saline to support plant life. Therefore, in order to maintain productivity, excess water must be applied to wash out an amount of salt equal to the amount contained in the applied water. The application of excess water, termed the leaching requirement, is directed at maintaining a salt balance within the plant root zone.

In humid climates, leaching is accomplished by the excess of percolating rain and snow-water. In arid climates there is no such natural excess, and the leaching must be accomplished by application of irrigation water in excess of the normal crop growth requirements.

The amount of irrigation water needed for leaching increases in proportion to the salinity concentration of the applied irrigation water. Any increase in the salinity of an irrigation water supply therefore results in an economic penalty since more water is required for equivalent service. This is a large, although sometimes unrecognized, economic loss caused by degraded irrigation water.

Combating the effects of saline irrigation water by leaching assumes that the soil will accept an increase in the amount of irrigation water applied. For the porous soils of the arid or semi-arid areas of the Southwest, this assumption is generally valid.

There are two alternative courses an irrigation water user may follow when confronted with degradation in the quality of his water supply: (1) apply more water to the fields and thereby maintain crop yields, or (2) maintain present water use and thereby suffer a decrease in crop yields. Obviously, there are disadvantages in doing either.

If additional water necessary for leaching is not available, the irrigator will have to either: (1) irrigate the same acreage and suffer a decrease in crop yields, or (2) take some acreage out of production and use the water previously applied to this acreage to leach the remaining acreage in order to maintain crop yields. Either alternative results in an economic loss to the water user, comparable to that suffered when additional water is available for leaching.

Where additional water is available for leaching several other associated economic detriments are incurred. As the applied irrigation water becomes more saline, greater and greater volumes of water are needed for leaching to maintain the salt concentration in the plant root zone at a satisfactory level. In some areas, the application of greater volumes of water may make it necessary to install artificial drainage facilities, such as open drains or buried tile drains. Such drainage facilities can represent a substantial cost to the irrigator.

Water percolating through the plant root zone will remove applied fertilizers as well as mineral salts. The nitrate fertilizers are especially susceptible to loss this way because of their high solubility. As additional water is applied for leaching, an additional amount of fertilizer must be applied to the land to offset the loss of fertilizer dissolved by the additional leaching water.

Finally, when additional water has to be applied for leaching purposes, more frequent applications of water are normally required causing increased labor costs.

The second characteristic of irrigation water that must be considered is the relative proportion of sodium to other cations. The alkali hazard involved in using irrigation water is determined by the absolute and relative concentrations of cations in the water. Soluble inorganic constituents in irrigation water react with soils as ions rather than as molecules. Calcium and magnesium in proper proportions maintain soil in good condition of tilth and permeability. The opposite is true if sodium predominates. In the soils of arid and semi-arid regions, calcium and magnesium are the major cations held in the soil in exchange form. Under normal use these soils have a favorable physical condition for root and water percolation. In situations where sodium is predominant, the soil pores begin to seal resulting in a decrease in permeability.

It is easier for calcium to replace sodium in the exchange complex than vice versa. Unless the sodium of the soil solution is in considerable excess of the calcium no reaction will occur. The soil solution is always more concentrated than the applied irrigation water. If the amount of magnesium is high in proportion to the total replaceable cations of the soil, more sodium will be absorbed than if calcium is the only divalent cation present.

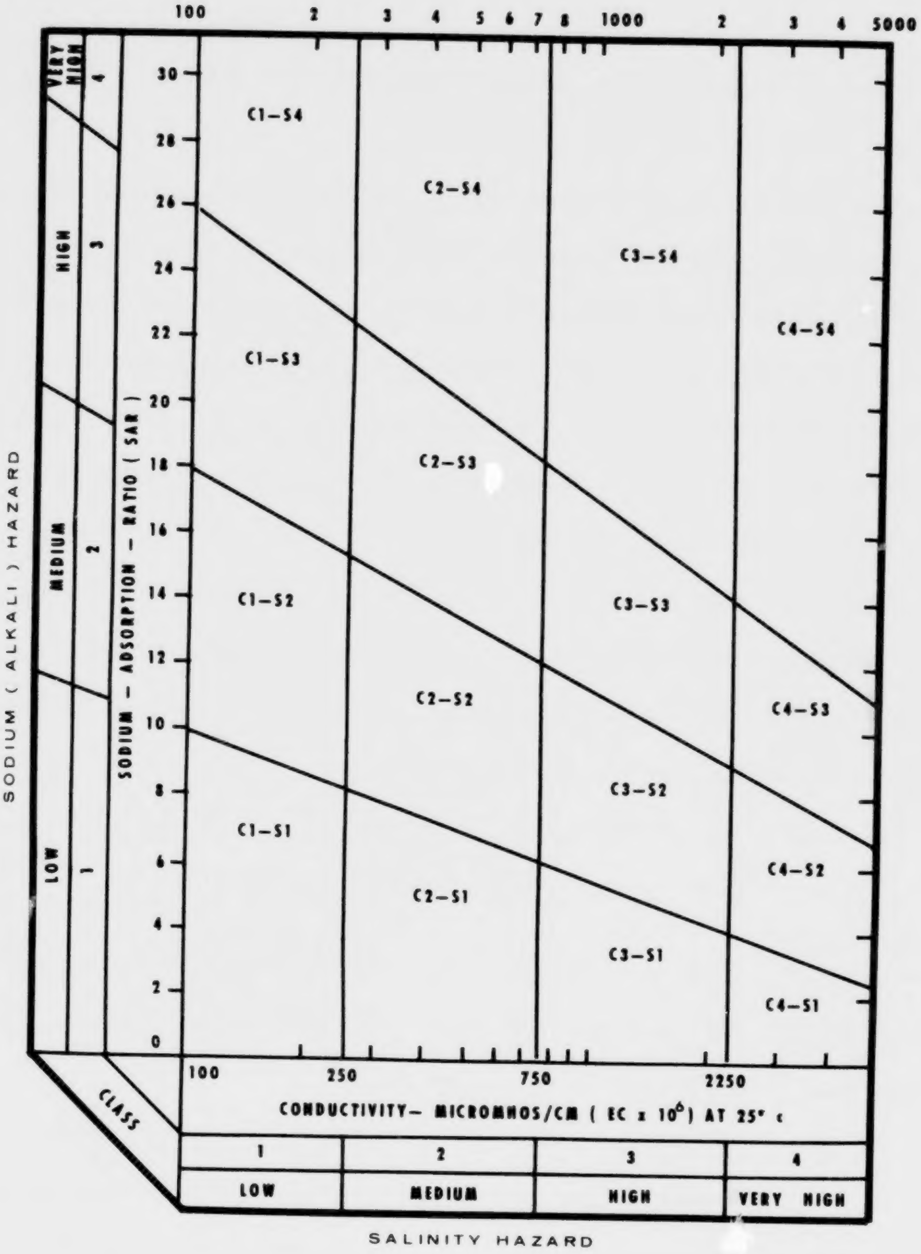
The sodium adsorption ratio (SAR) has been developed to express the sodium hazard in irrigation water. The ratio expresses the relative activity of sodium ions in the exchange reaction with ions in the soil. The ratio is defined by the following equation:

$$\mathrm{SAR} = \frac{\mathrm{Na}^{+}}{\sqrt{\dfrac{(\mathrm{Ca}^{++} + \mathrm{Mg}^{++})}{2}}}$$

where Na^{+}, Ca^{++}, and Mg^{++} represent the concentrations in milliequivalents per liter of the respective ions. The SAR, in other words, is related to the adsorption of sodium by the soil.

The Salinity Laboratory has set up classifications of irrigation water in regard to the sodium hazard. The sodium hazard varies with the salinity concentration of the irrigation water. The classifications are shown in Figure 1.

Low sodium water can be used without much danger of development of harmful levels of sodium. However, some sodium sensitive crops such as stone fruit trees and avocados may be injured. An appreciable sodium hazard may develop in fine textured soils with the use of medium sodium



Note: Reproduction from U. S. Department of Agriculture, U. S. Salinty Laboratory, "Saline and Alkali Soils," Agriculture Handbook No. 60, 1954; Figure 25(10)

Figure 1. Diagram for the Classification of Irrigation Waters

water, especially under low leaching conditions. The presence of gypsum in the soil is helpful. High sodium water may produce harmful effects in most soils and will require special soil management such as good drainage, high leaching, and addition of organic matter. A very high sodium water is generally not satisfactory for irrigation except at low or medium salinity concentrations, where the solution of calcium from the soil or the use of gypsum or other additives make the use of such water feasible.

A third characteristic of irrigation water that must be considered is the boron concentration. This element is present in most natural waters with concentrations varying from traces to several milligrams per liter. Boron is essential to plant growth but is very toxic at concentrations only slightly above optimum. Eaton[1] found that many plants made normal growth in sand cultures with a trace of boron, but injury often occurred with cultures containing one mg/l.

In waters containing high concentrations of bicarbonate ion, as the soil solution becomes more concentrated there is a greater tendency for calcium and magnesium to precipitate as carbonates. This reaction does not usually go to completion, but it may go far enough to cause a decrease in the concentrations of calcium and magnesium with an increase in the relative proportion of sodium.

Eaton's work[2] resulted further in classification of waters with regard to the bicarbonate ion hazard using the "residual sodium carbonate" concept. This classification is shown in Table 5. Waters classified as marginal may be used if good management is practiced.

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[1] Eaton, F. M., "Deficiency, Toxicity and Accumulation of Boron in Plants," Journal Agricultural Research, Volume 69, Illustration 1944, pp. 237-277. (Reference No. 12)

[2] Eaton, F. M., "Significance of Carbonates in Irrigation Waters," Soil Science, Volume 69, 1950, pp. 123-133. (Reference No. 13)

In appraising the quality of irrigation water, the salinity hazard should be considered first, followed by the alkali hazard. Next, consideration should be given to boron or other possible toxic elements, followed by consideration of the bicarbonate ion concentration.

Table 5. Classification of Irrigation Water as to Bicarbonate Ion Hazard

Classification	Residual sodium carbonate in milliequivalents
Probably safe	< 1.25
Marginal	1.25 - 2.5
Not suitable	> 2.5

Livestock

Information on livestock tolerance to mineralized water was dervied from the "Report of the Committee on Water Quality Criteria" published by the Federal Water Pollution Control Administration, U. S. Department of the Interior.(14) The following discussion of the effect of total dissolved solids on livestock is also based on "Water Quality Criteria"(2) published by the California Water Quality Control Board.

It has been assumed that water safe for human use is also safe for livestock, and it has been recommended that such water be used for best stock production. However, it appears that stock animals have higher tolerances than humans, although they may differ in tolerance to particular substances. The use of highly mineralized water may result in physiological disturbances such as gastrointestinal symptoms and death. In animals, lactation and reproduction can be affected by use of water of high concentrations of unfavorable minerals. Milk and egg production also may be reduced or interrupted. Animals can adjust, within limits, to consumption of saline water that at first they refuse to drink. However, a sudden change from good water to highly saline water can cause acute salt poisoning and rapid death. The salt tolerance of an animal depends upon several factors including species, age, physiological condition, season of the year, diet, and the quality and quantity of salts present. Officials of the Department of Agriculture and the government chemical laboratories of Western Australia have established threshold concentrations for livestock water in Western Australia as shown in Table 6.

The effect of water containing heavy concentrations of chlorides, sulfates, carbonates, bicarbonates, sodium, calcium, and/or magnesium is due to the total salts present rather than the toxic effect of any one constituent. Alkali salts are more harmful than neutral salts, sulfates more harmful than chlorides, and magnesium chloride more harmful than calcium or sodium chloride. Some of the states have set classifications for stock water, as shown in Table 7. Except for short reaches of some tributary streams, the waters of the Colorado River Basin would fall within the highest quality classification.

Some particular salts are toxic to animals, even in very low concentrations. Compounds causing trouble in water are fluorides, nitrates, and salts of selenium and molybdenum. The effect of fluoride on animals is similar to that for humans, and 1.0 mg/l is the threshold value below which no harm results. Nitrates in livestock water have been harmful in lower concentrations than mixtures of chlorides and sulfates of alkaline metals. When the salinity concentration of livestock water

Table 6. Safe Upper Limits of Salinity Concentrations Recommended for Livestock Water in Western Australia

Animal	Threshold Salinity Concentration in mg/l
Poultry	2,860
Pigs	4,290
Horses	6,435
Cattle, dairy	7,150
Cattle, beef	10,000
Adult dry sheep	12,900

Table 7. Salinity Classifications for Livestock Water Set by Several States

State	Classification and Concentration in mg/l			
Montana	good 0-2500	fair 2500-3500	poor 3500-4500	unfit > 4500
South Dakota	excellent 0-1000	good 1000-4000	satisfactory 4000-7000	unsatisfactory > 7000
Colorado	acceptable 0-2500	--	--	--

exceeds 570 to 1,000 mg/l, the nitrate concentration should be watched carefully. The principal hazard of molybdenum and selenium results from its uptake in pasture grasses and concentration in the plant tissues. If copper is fed to cattle in some form along with molybdenum, the toxicity of the molybdenum appears to be reduced. The concentration of these minor elements in waters of the Colorado River and tributaries are generally below the threshold values. In recent years the fluoride concentrations at two stations on the Gila River were well above the threshold value, being as high as 4.2 mg/l. These two stations are the Gila River below Gillespie Dam and the Gila River at Kelvin, Arizona.

NON-CONSUMPTIVE USES

Non-consumptive uses of water include hydroelectric power generation, navigation, water-oriented recreation, fish and wildlife, silt control, general water quality control, and ground water recharge. Detriments to navigation and power generation certainly should be insignificant for the projected rise in salinity (from about 800 to 1,200 parts per million at Imperial Dam). Similarly, little or no detrimental effect can be envisaged on native fauna, water sports, recreation and esthetic enjoyment. Although minor detrimental effects are expected for two categories of non-consumptive use--(1) fish and wildlife, and (2) ground water recharge--these effects are not expected to have significant economic impact on the Basin for the anticipated range of salinity concentrations.

Fish and Aquatic Life

Fish and aquatic life are affected by dissolved substances in two basic ways:

(1) Substances such as aluminum, iron, manganese, zinc, and copper can be toxic to some species of fish in very low concentrations;

(2) Other substances exert lethal osmotic pressures at high concentrations. A pure solution of NaCl is lethal to fresh-water fish at concentrations in excess of 7,000 ppm, the concentration at which the fish's osmotic blood pressure (six atmospheres) is exceeded.

Criteria for the required quality of fresh water supply that will support a good mixed fish population were developed by Ellis, who proposed the following limits:(15)

1. Dissolved oxygen, not less than 5 mg/l;
2. pH, approximately 6.7 to 8.6, with an extreme range of 6.3 to 9.0;
3. Specific conductance at 25° C, 150 to 500 mho X 10^{-6}, with a maximum of 1,000 to 2,000 mho X 10^{-6} permissible for streams in western alkaline areas;
4. Free carbon dioxide, not over 3 cc per liter;
5. Ammonia, not over 1.5 mg/l;
6. Suspended solids such that the millionth intensity level for light penetration will not be less than 5 meters.

In the absence of toxic substances or pollutants, the water described above is favorable, not merely sublethal, for a mixed warm-water fish population and its food organisms. It must not, however, be assumed that fish are not found or cannot survive in waters with concentrations beyond these limits.

Measures of total dissolved solids, whether in terms of parts per million, conductivity, or osmotic pressure equivalents, are inadequate as an index of toxicity. Therefore, biossay techniques are used to determine the degree of dilution essential for the safe disposal of brines and other complex wastes which are high in dissolved solids.

After a review of available biological data and a limited amount of field investigations, it can be concluded that the expected future increases in salinity per se within the Colorado River Basin will have very little or no effect on the fish and aquatic life. However, the Salton Sea of Southern California, whose inflow is originally derived from the Colorado River, is facing possible extinction to its fish and aquatic life if present trends in salinity increases prevail into the future. Present salinity of the sea is about 33,000 mg/l, or nearly that of sea water. Chloride concentrations approximate 14,000 mg/l. It has been estimated(16) that salinity will increase about 400 mg/l per year. Other researchers have indicated that salinity can be expected to increase at more rapid rates. At the rate of 400 mg/l per year the salinity of the sea will reach 40,000 mg/l in 1975 and 50,000 mg/l in the year 2000. While the total effects of such salinity levels on the biota of the sea is not definitely known, the State of California Department of Fish and Game believe that the food chain will be seriously affected and possibly destroyed sometime around 1980-1990. The problems of the Salton Sea and possible solutions are currently being considered by several groups.

Ground Water Recharge

Underground basins are a major source of water supply in three of the seven Colorado River Basin states. The ground water supply proportion of the total water supply in the States of Arizona, California, and New Mexico is 69 percent, 36 percent, and 58 percent, respectively. In Southern California ground water comprises about 50 percent of the total supply, or approximately 1,400,000 acre-feet per year, and 300,000 to 400,000 acre-feet of this amount is in excess of the estimated safe yield from natural recharge.

Imported water has a large and growing role in the replenishment of ground water basins in Southern California. This replenishment is the intentional or managed recharge, and not the adventitious recharge accomplished by disposal of waste water on land. The amount of Colorado River water used for direct recharge of ground water basins in Los Angeles and Orange counties was 346,000 acre-feet in 1962-63 and 300,000 acre-feet in 1963-64. The use of Colorado River water for this purpose is declining because of the growing demand for domestic and industrial water. Leading authorities in the water resources management field in California foresee a continual decline in the amount of Colorado River water available for recharge. If and when the Central Arizona Project is completed, Colorado River water will probably not be available for direct recharge in California because all of the Metropolitan Water District entitlement will be needed for municipal and industrial uses.

The Central Arizona Project planning documents indicate that imported Colorado River water will not be used for direct replenishment. It is anticipated that the Project will provide a net delivery of

1,020,000 acre-feet annually. Municipal and industrial users will consume approximately 250,000 acre-feet of this net delivery, and the remainder will be used for supplemental irrigation. A fraction of this amount will certainly replenish ground water basins by percolation, but this fraction will contain nearly all of the dissolved salts in the imported water, plus increments added in a cycle of municipal, industrial or agricultural use.

The effects of the quality of recharge water upon a ground water body have been recognized only in recent years. In the operation of any ground water reservoir large amounts of mineral salts may be brought in by tributary inflow; both surface and underground. As a result of human activities other salts are brought into the area in the form of agricultural chemicals, inorganic fertilizers, and numerous chemicals of commerce. A considerable portion of these latter forms of salt may percolate through the upper soil horizon to the ground water.

Since the ground water body is of finite size, it is evident that a stable condition of quality requires salts to be removed in the same amount that enter the Basin. This condition is known as salt balance. In nature it is achieved by removal of the dissolved salts in subsurface outflow or in rising ground water (springs) which contribute to surface streams. In developed areas the process may be modified considerably by well pumping, import or export of water, outfall sewers, etc., but the principle is unchanged.

The process can be expressed mathematically for an idealized case by the simple relation,

$$\frac{dx}{dt} = I - O$$

where x = the total weight of dissolved salts in a ground water basin at any time *t*,

I = the rate of inflow or addition of salts

O = rate of outflow of salts.

If the natural balance is altered by the importation of water containing dissolved mineral salts, the outflow of salts must be increased; otherwise, water quality will deteriorate. The increased burden of salts can be removed in three ways: (1) by an increased outflow of water of unchanged salinity concentration, (2) by an unchanged outflow of water with an increased proportion of dissolved salts, or (3) by some condition intermediate between these two.

If the quality of the imported water becomes degraded in time, i.e. attains a higher salinity, it is apparent that provision must be made for removal of the new burden of salt. A degradation of the imported source engenders two alternative economic penalties. Either more water must be wasted in outflow from the Basin in order to maintain a stable water quality in the underground aquifers, or the salt concentration in those aquifers will build up, perhaps to the point where the ground water will become unfit for domestic, industry or agriculture uses. This is an issue in the proposed Central Arizona Project. A worsening of the mineral quality of Colorado River water might generate these undesirable effects: (1) the need for higher outflow, with consequent waste of water and drainage expense, and (2) a salinity increase in the ground water basins in the Project area.

Specific limits on the quality of water for ground water recharge have rarely been recommended or imposed by regulatory agencies. Numerous factors must be taken into consideration in the establishment of such limits including: (1) the quality of the recharge waters, (2) a reasonable allowance for effects of water use in their area of origin, (3) the existing quality of water in the aquifers to be replenished, and (4) the beneficial uses of water within the overlying areas.

In the late 1950's a State of California regulatory agency(17) established mineral quality objectives for the underground and surface water outflows in the Bunker Hill Basin and in the Santa Ana River. These objectives were designed to preserve the quality of those waters for replenishment of downstream ground water basins. The limiting values adopted are shown in Table 8.

In 1955 a board of consultants to the California Department of Water Resources recommended chemical and physical quality standards for water which was to be exported from the Sacramento-San Joaquin Delta to Southern California.(18) Major uses of the exported water included ground water replenishment, which was undoubtedly an influential factor in determining the quality limits which are shown in Table 9.

The results of a water resources study(19) made several years ago by the Department of Water Resources of the State of California illustrate the importance water quality may have in ground water recharge. An analysis was made of the effects of differences in quality between two alternative replenishment supplies for certain ground water basins in Riverside and San Bernardino Counties. The economic penalty incurred by using the poorer of the two sources was estimated to be about four million dollars annually.

Table 8. Proposed Ground Water Quality Objectives for the Bunker Hill Basin and the Santa Ana River in California

Constituent	Maximum Tolerable Concentration (parts per million) Bunker Hill Unit	 Santa Ana River at Prado
Total dissolved solids	500	800
Total hardness as $CaCO_3$	300	400
Chloride	60	175
Bicarbonate	300	320

Table 9. Recommended Chemical and Physical Quality Standards for Water to be Exported to Southern California from the Sacramento-San Joaquin Delta

Item	Limit
Total dissolved solids	400 ppm
Electrical conductance @ 25° C	600 micromhos
Hardness as $CaCO_3$	160 ppm
Sodium percentage	50%
Sulphate	100 ppm
Chloride	100 ppm
Fluoride	1.0 ppm
Boron	0.5 ppm
pH	7.0 - 8.5
Color	10 ppm

The actions cited above serve to show that salinity or mineral quality is an important consideration in waters used to replenish ground water reservoirs, and that poor quality of such recharge waters is likely to engender economic loss. Although methods can be derived to evaluate such losses, data for such an evaluation are quite limited. Therefore, no attempt was made to evaluate such effects in the Project's salinity studies of the Colorado River Basin.

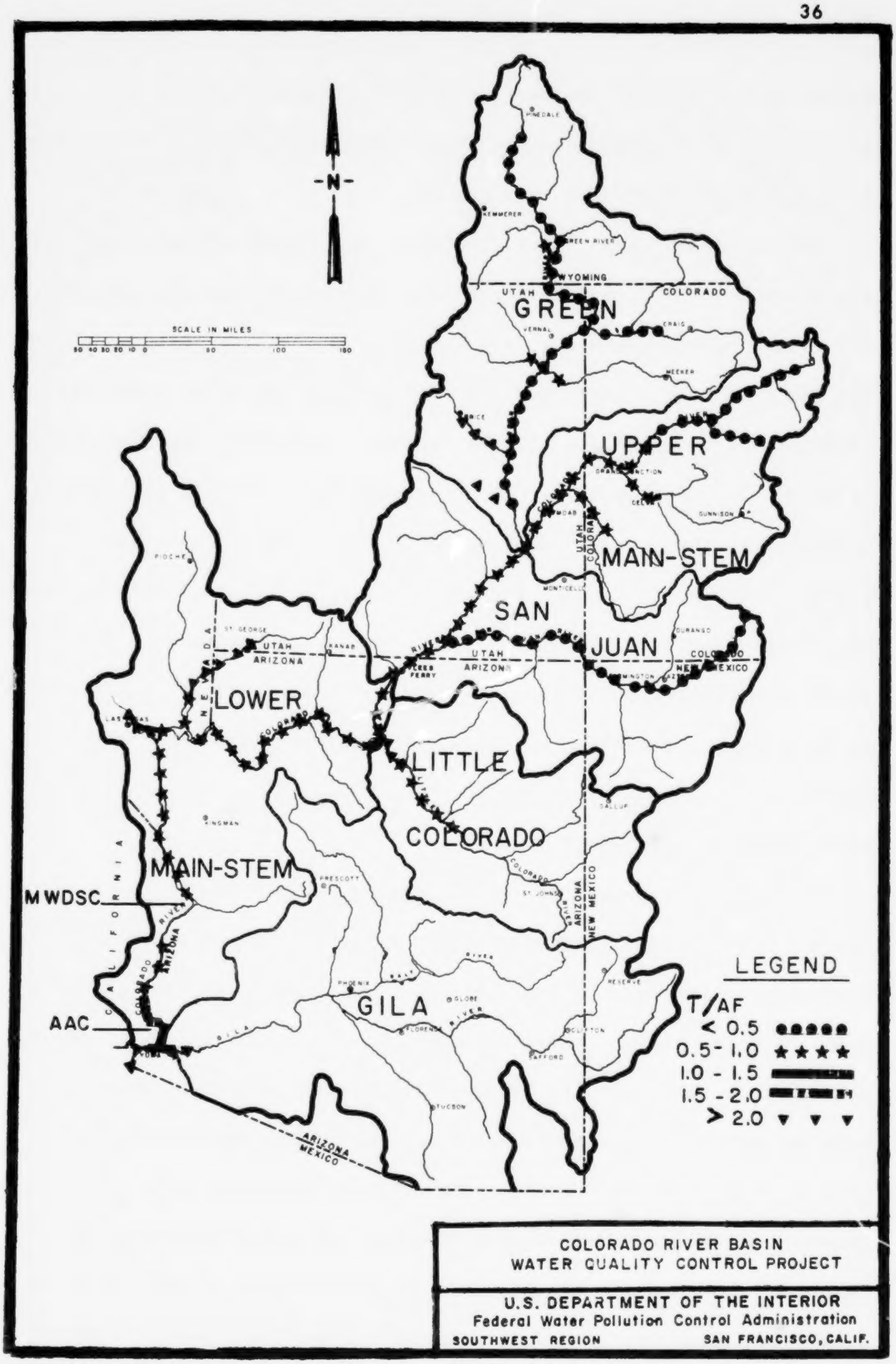
CHAPTER III. PRESENT AND FUTURE MINERAL QUALITY

PRESENT MINERAL QUALITY

The findings of field studies conducted by the Project to define present mineral quality and its causes are presented in Appendix A of the Project's Report entitled "Mineral Water Quality Problem in the Colorado River Basin." The purpose of this section is to summarize those findings and to relate them to methods used in the economic impact analysis

A summary of water quality, as defined by Project field studies during the period October, 1963, to May, 1966, is shown in Figures 19 through 46 of Appendix A. Although the overall findings of the Project studies were substantially identical to the 1956-1958 quality described above, local discrepancies were noted. Discrepancies of this type are quite common when two records based upon relatively short-duration studies are compared The value of short-term studies resides in refinement of cause-and-effect relationships; however, long-term records and analysis must be used to establish average or base qualities.

Average salinity concentrations existing in the Basin streams during the period from 1956 to 1958 are illustrated by Figure 2 Salinity increases progressively in the main stem of the Colorado from the headwaters to the mouth. With the exception of a few streams such as the Price, San Rafael and Dolores Rivers, mineral quality of major streams in the Upper Basin (upstream from Lees Ferry) is good, averaging less than 1 0 tons of dissolved solids per acre foot (T/AF). In the Lower Basin salinity increases more rapidly, reaching concentrations


N
SCALE IN MILES
50 40 30 20 10 0
50
100
150
PINEDALE
KEMMERER
GREEN RIVER
WYOMING
UTAH
COLORADO
GREEN
VERNAL
CRAIG
MEEKER
PRICE
UPPER
GRAND JUNCTION
DELTA
GUNNISON
MOAB
UTAH
COLORADO
MAIN-STEM
MONTICELLO
SAN
JUAN
DURANGO
COLORADO
NEW MEXICO
FARMINGTON
AZTEC
UTAH
ARIZONA
LEES FERRY
PIOCHE
ST. GEORGE
UTAH
ARIZONA
KANAB
NEVADA
LOWER
LAS VEGAS
COLORADO
LITTLE
COLORADO
GALLUP
KINGMAN
MAIN-STEM
CALIFORNIA
ARIZONA
MWDSC
PRESCOTT
COLORADO RIVER
ST. JOHNS
ARIZONA
NEW MEXICO
AAC
YUMA
PHOENIX
SALT
RIVER
GILA
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CLIFTON
SAFFORD
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TUCSON
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< 0.5 ● ● ● ● ●
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1.0 - 1.5
1.5 - 2.0
> 2.0 ▼ ▼ ▼
COLORADO RIVER BASIN
WATER QUALITY CONTROL PROJECT
U.S. DEPARTMENT OF THE INTERIOR
Federal Water Pollution Control Administration
SOUTHWEST REGION
SAN FRANCISCO, CALIF.

Figure 2. Mean Salinity Concentrations in the Principal Streams of the Colorado River Basin During the Period 1956 - 1958

exceeding 2.0 T/AF at the Mexican border. Diverse factors, both natural and man-caused, contribute to this pattern of mineral quality as described elsewhere in this report.

As discussed later in this chapter, a suitable salinity base was established to which a comparison of projected quality was made. Since any record of water quality is a function of changing patterns of water use and pollution discharge, it was determined that a mathematical model of the Basin should be constructed to similate long-term mineral quality. The development of the model and the resulting analyses are described in the section of this chapter entitled, "Methods and Assumptions Used to Project Mineral Quality." Results of the analyses based upon the 1942-1961 hydrologic period are summarized in Table 10. These results, corrected for 1960 condition of water use, are referred to as present, or 1960, mineral water quality in the remainder of the report.

AREAS AFFECTED BY MINERAL QUALITY

The greatest impact of mineral quality occurs in the Lower Colorado Basin and Southern California water service area where water usage is much greater than in the Upper Basin. The relative concentration of population and irrigation water demands in the Upper and Lower Basins are shown in Table 11. It is clear that there is a preponderance of population and irrigation in the Lower Basin and, consequently, a greater requirement for water. The areas of greatest water use, or the location of largest water-demand centers, are below Lees Ferry and comprise the subbasins of the Lower Main Stem (LMS) of the Colorado with urban territory centered in Las Vegas and Yuma; the Gila Basin,

Table 10. Total Dissolved Solids Concentrations in the Colorado River at Selected Stations (1960)

Stream Mile (Measured from Southern International Boundary)	Station	Total Dissolved Solids[a] (Mg/1)
716	Lee Ferry, Arizona	558
625	Grand Canyon	631
356	Hoover Dam	697
200	Parker Dam	684
50	Imperial Dam	759
28	Yuma, Arizona	2,632[b]

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a/ Results of flow and salt routing model based on 1942-1961 hydrologic period.

b/ Time-weighted mean value for water year 1962, including drainage from Wellton-Mohawk Project.

Table 11. Population and Irrigation Water Use in the Colorado River Basin and Southern California Water Service Area

Area	1960 Population (1000)	Estimated Deliveries of Water for Irrigation (acre-feet per year)
Upper Basin above Lee Ferry	338	2,800,000[a]
Lower Basin below Lee Ferry		
Little Colorado Subbasin	106	--
Gila Subbasin	1,159	--
Lower Main Stem Subbasin less Imperial County, California	236	--
Southern California Water Service Area	8,900[b]	--
Lower Basin plus Southern California Water Service Area	10,401	6,323,000[c]
Percent of Total in Upper Basin	3	31
Percent of Total in Lower Basin and Southern California	97	69

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a/ Based upon an assumed 60 percent irrigation efficiency, a high value, and a total estimated consumptive use of 1,685,000 acre-feet. See report of the U. S. Department of the Interior, "Quality of Water, Colorado River Basin," January 1965, pp. 10-11. (Reference No. 20)

b/ Comprises the 1963 population of the Metropolitan Water District plus appropriate parts of Imperial County.

c/ Comprises 4,690,000 acre-feet in Lower Basin plus 1,633,000 acre-feet in the Southern California Water Service Area. See Table 8 of U. S. Department of the Interior report, "Pacific Southwest Water Plan," August 1963. (Reference No. 21) with large populations in Phoenix and Tucson; and the Southern California (SC) water service area. The latter area covers all of Southern California lying outside the natural drainage basin of the Colorado River which is served by water exported from that stream. It includes parts of Los Angeles and San Diego served by the Metropolitan Water District (MWD) of Southern California and the Imperial and Coachella Valley lands and communities which receive water via the All American Canal.

Present use of Colorado River water in Arizona is limited to land riparian to, or located only a short distance from the river. The principal users are the Colorado River Indian Reservation (CRIR) with consumptive water use in 1960 of about 185,000 A.F. and the several subdivisions of the Gila and Yuma Projects with consumptive water use in 1960 of about 640,000 A.F.(22) The only sizeable diversion for urban use is for the city of Yuma, which currently uses about 8,000 A.F. per year. The Pacific Southwest Water Plan of the Department of the Interior provides for considerable expansion of irrigation on the CRIR, with a future water requirement estimated to reach 380,000 A.F. annually by the year 2000(21). These areas are all sensitive to changes in mineral quality of water at the present time.

The Central Arizona Project (CAP) of the Department of the Interior will, when completed (probably about 1979), divert a gross volume of about 1,600,000 A.F. annually from the Colorado River at Lake Havasu. This diversion will be decreased to 676,000 A.F. annually by the year 2030. Delivery to municipal and industrial users in Phoenix and Tucson will make up five percent of the diversion and is expected to increase to 50 percent in 2030. The remainder of the delivery will be for agricultural service in the rural areas of Maricopa and Pinal Counties.(23) These uses, as well as the replenishment of ground water bodies in the area, will be affected by changes in mineral quality of the Colorado River supply after 1975 and the associated importation of over one million tons of salt annually.

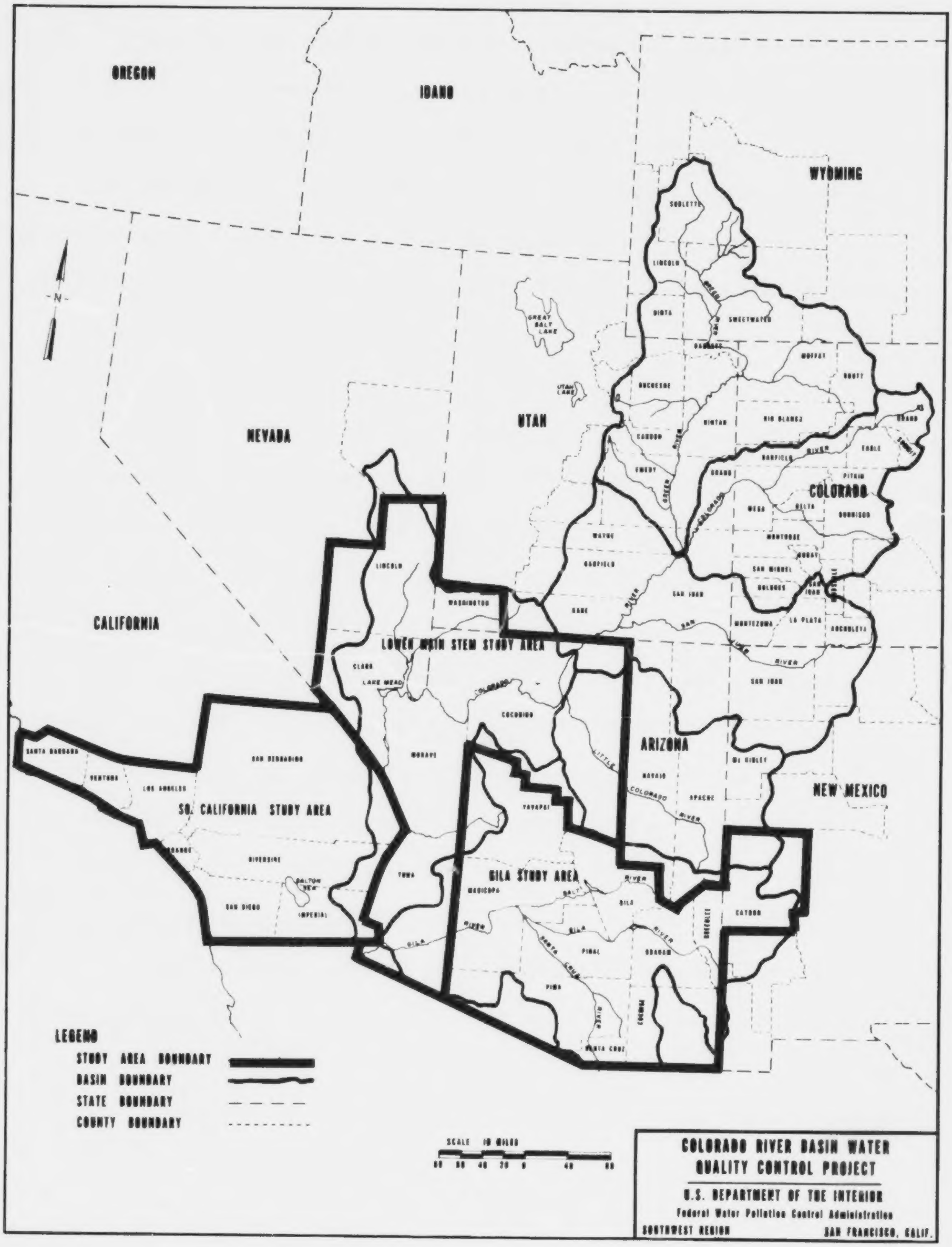
Although the principal effects of future degradation in mineral quality will be experienced in the Lower Basin, two Upper Basin areas will experience pronounced salinity increases in surface water supplies because of future economic and water resources developments. These are the Duchesne Basin in Utah and the upper basin of the San Juan River above Shiprock, New Mexico.

The first, the Duchesne River Basin located in northeastern Utah, is made up of portions of Wasatch, Duchesne, and Uintah Counties. Total irrigated acreage amounts to about 140,000 acres, of which about 62,000 acres is Indian land. According to estimates of the Bureau of Reclamation, (20) the average dissolved solids concentration in the Duchesne River near Randlett, Utah, will rise from a present-modified value of 0.98 T/AF (720 mg/l) to 1.59 T/AF (1170 mg/l) following construction of the Bonneville and Upalco Units of the Central Utah Project. Municipal and industrial water supplies are obtained mainly from groundwater. Thus, the impact of mineralized Colorado River water upon these users will be practically nil.

The second area in the Upper Colorado Basin, the Upper San Juan subbasin, comprises all or portions of 22 counties in southern Colorado, northern New Mexico, and southeastern Utah. Like the first area, population is sparce and agriculture dominates the economy. Unlike the Duchesne area, the gas and petroleum industry has replaced agriculture in importance in some areas. In the San Juan River near Bluff, Utah, progressive small increases in salinity are anticipated following construction of the Navajo, Hammond, and Florida Projects, and a larger rise under operation of the San Juan-Chama and the Navajo Indian Irrigation Projects. The maximum increase expected is 0.38 T/AF, of which the greater part, 0.35 T/AF, would result from consumptive use and leaching of salts from irrigated lands on the Navajo Reservation. The magnitude of the future water quality change will be too small to have appreciable effect on the limited amount of irrigated land downstream of the anticipated increase. The municipal penalty costs are also insignificant due to the small population and the relatively low hardness of the water.

Economic analysis of the Duchesne and San Juan areas indicated that a significant impact of salinity on water uses is not likely to be incurred by any Basin area unless it possesses the following characteristics in combination with appreciable future water quality degradation of the Colorado River: (1) contains large population centers, and/or (2) has a high level of industrial and irrigated agriculture development. After studying various areas within the Colorado River Basin and applying the above criteria, it became fairly obvious that significant physical and economic impacts were most likely to occur in the Lower Colorado River Basin and its contiguous water service areas. Three study areas, as shown in Figure 3, were therefore delineated below Lees Ferry.

It should be noted that the study area boundaries do not always


OREGON
IDAHO
WYOMING
NEVADA
UTAH
COLORADO
CALIFORNIA
ARIZONA
NEW MEXICO
N
GREAT SALT LAKE
UTAH LAKE
SUBLETTE
LINCOLN
UINTA
SWEETWATER
DAGGETT
MOFFAT
ROUTT
DUCHESNE
UINTAH
RIO BLANCO
GRAND
EAGLE
SUMMIT
CARBON
GARFIELD
PITKIN
EMERY
MESA
DELTA
GUNNISON
MONTROSE
OURAY
SAN MIGUEL
DOLORES
SAN JUAN
WAYNE
GARFIELD
KANE
MONTEZUMA
LA PLATA
ARCHULETA
McKINLEY
NAVAJO
APACHE
LINCOLN
WASHINGTON
CLARK
LAKE MEAD
MOHAVE
COCONINO
YAVAPAI
GREEN RIVER
COLORADO RIVER
SAN JUAN RIVER
LITTLE COLORADO RIVER
SALT RIVER
GILA RIVER
SANTA CRUZ RIVER
LOWER MAIN STEM STUDY AREA
SO. CALIFORNIA STUDY AREA
GILA STUDY AREA
SANTA BARBARA
VENTURA
LOS ANGELES
SAN BERNARDINO
ORANGE
RIVERSIDE
SAN DIEGO
IMPERIAL
SALTON SEA
YUMA
MARICOPA
GILA
GREENLEE
CATRON
PINAL
GRAHAM
PIMA
COCHISE
SANTA CRUZ
LEGEND
STUDY AREA BOUNDARY
BASIN BOUNDARY
STATE BOUNDARY
COUNTY BOUNDARY
SCALE IN MILES
80 60 40 20 0 40 80
COLORADO RIVER BASIN WATER
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Federal Water Pollution Control Administration
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SAN FRANCISCO, CALIF.

Figure 3. Location of Salinity Impact Study Areas

conform to hydrologic basins. Since economic data are most often reported by civil areas rather than natural drainage areas, it was necessary to alter boundaries somewhat to achieve the objective of analyzing economic impacts. The Lower Main Stem study area includes Clark and Lincoln Counties in Nevada; Washington County in Utah; and Mohave, Coconino, and Yuma Counties in Arizona. All California land in the Lower Main Stem hydrologic subbasin is included in the Southern California study area. This study area includes the following counties: Santa Barbara, Ventura, Los Angeles, San Bernardino, Orange, Riverside, San Diego, and Imperial. The Gila study area includes Cochise, Gila, Graham, Greenlee, Maricopa, Pima, Pinal, Santa Cruz, and Yavapai Counties in Arizona, and Catrol County in New Mexico.

METHODS AND ASSUMPTIONS USED TO PROJECT MINERAL QUALITY

In order to calculate economic impacts associated with mineral quality degradation, it was necessary to establish a base quality and to project future qualities. Since long-range effects were to be assessed, including one projection to the year 2010, the decision was made to use a long-term average for base quality. Future changes in mineral quality would then be compared to the base quality in order to quantify the effect of anticipated development upon future water users. Furthermore, it was decided that the methods used to calculate future quality should be consistent with those used to determine base quality. In any such determination of mineral quality there are three factors which are critical: (1) the basic flow or hydrology of the system; (2) location and magnitude of demands for water; and (3) the location and magnitude of salt sources. These three factors must be known or estimated for each target year for which the economic impact of water quality is to be determined.

Hydrology

A long-term hydrological period of flow was selected as a base condition for several reasons, the first of which is that short-term fluctuations may be accomodated within the Basin.(24) It is well known that short-term variations in stream quality are dampened by the large mainstream reservoirs and that salts can be stored in the soils of the water-producing and water-using areas.

Secondly, it was felt that economic losses due to water quality problems of short duration might be balanced against bountiful returns obtained in years of good water quality. Long-term conditions, however, would lead to permanent changes in water-use practices and would, therefore, be reflected in detectable economic effects.

A third reason for using a long hydrologic period is that mean flows for periods longer than five years may be treated as stochastic variables, which allow the application of the principals of elementary statistics to the virgin flow or modified flow data.

Fianlly, augmentation of flow through storage regulation may be ignored for long-base periods since it evens out flow variability. A study of the 20-year yield from present and proposed storage has not been made;1/ however, it has been assumed that the 20-year mean virgin

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1/ For a study of the firm yield of the Upper Basin reservoir system, see p. 21 of reference 26. Their estimate of the firm yield from Upper Basin storage is 13.8 MAF of regulated delivery. Some additional yield could presumably be developed from Lower Basin reservoirs.

flow could not be effectively augmented by releases from storage.

The period 1942-1961, which has a mean annual virgin flow at Lees Ferry, Arizona, of 13.8 million acre-feet (MAF), was chosen as the lowest available consecutive 20 years of record in 1963 when the Project study was started. This choice is consistent with the practices of basing water quality studies on extreme low flow conditions when there is adequate assurance that the extremes are significant. There is a probability of about 0.13 that this value will not be exceeded by any 20-year mean virgin flow, and a probability of about 0.62 that the virgin flow for any one year will exceed 13.8 MAF.

Selection of a longer period of record or of any other 20-year period of record would yield a slightly higher mean annual virgin flow and mean annual salt burden. If water-use conditions were such that the increased flow could be consumptively used above Lake Powell, predicted salinity concentrations would be higher than for the 1942-1961 period of record since a larger salt burden would be carried by essentially the same stream flow below Lees Ferry. However, operational hydrology studies indicate that existing and planned holdover storage above Lake Powell would not be adequate to permit full utilization of excess supply in periods of extremely high runoff. Thus, the larger salt load produced during such periods would be carried into Lakes Powell and Mead in high

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It is also possible to augment the in-basin storage by exporting water to holdover storage in other basins as is done in the Colorado Big-Thompson Project. Thus, one might realistically expect the long-term yield to approach the long-term mean flow; however, the water will not be available as a uniform regulated annual flow. Thus, questions concerning the impact of high and low flow sequences are important.

high quality runoff resulting in lower mean salinity concentrations in the Lower Basin.

Additional hydrologic information for the Upper Basin was taken from Geological Survey Professional Papers 441 and 442 (Iorns).(27) The historic flows published in the Geological Survey Water Supply Papers were compiled for the station at Lees Ferry during the base period and were then modified to 1960 conditions of use in the Upper Basin. These modified values were used as the factors to adjust Iorns' data (1914-1957 period) to the 1942-1961 period. For the Lower Basin the historic flows recorded at U. S. Geological Survey gaging stations during the base period were modified to 1960 conditions.

Water Demand

Present water-use data were obtained by means of a limited number of field interviews and an extensive search of current literature. Municipal water-use data were obtained from the publications of agencies like the Bureau of Reclamation (BR) and the Arizona Water Company. For the most part, industrial and agricultural water-use data were obtained by means of field interviews.

Future municipal water-use projections were obtained from the current literature wherever possible (BR and Arizona Water Company). Industrial water-use projections were obtained by assuming a relationship between future water use and economic production. Consideration was also given to the industrial water-use projections made by agencies like the BR. Future water resource projects that were included in the analysis are shown in Table 12. Methods used to determine future water-use requirements for irrigated agriculture are described in another part of this chapter.

Table 12. Future Water Resources Projects[a]

Project	Completion Date	Acreage	Total Flow (acre-feet)	Total Salt Load (tons)
UPPER COLORADO RIVER BASIN				
Lyman, Wyoming	1980	0	10,000	
Silt, Colorado	1980	2,120	6,000	3,964
Emery County, Utah	1980	770	17,000	1,925
Hammond, New Mexico	1980	2,000	5,000	3,420
Seedskadee, Wyoming	2010	58,775	165,000	129,305
Central Utah, Utah				
Bonneville Unit	2010		166,000	- 31,000
Jensen Unit	1980	500	10,000	1,220
Upalco Unit	1980		20,000	
Uinta Unit	2010		20,000	
Denver, Englewood, Colorado Springs & Pueblo Diversions	2010		234,000	- 16,000
M&I Green Mountain	1980		12,000	
Independence Pass Expansion	1980		14,000	- 3,000
Homestake Project, Colorado	2010		74,000	- 10,000
Hayden Steam Plant	2010		12,000	
Bostwick Park, Colorado	1980	1,320	4,000	673
Savery-Pot Hook, Wyoming-Colorado	1980	21,920	38,000	26,304
Fruitland Mesa, Colorado	1980	16,520	28,000	8,425
Expansion Hogback	1980		10,000	
Utah Construction Company, New Mexico	1980		25,000	
Westraco-Utah Power & Light Company, Wyoming	1980		36,000	
San Juan-Chama, Colorado-New Mexico	1980		110,000	- 14,000
Navajo Indian Irrigation, New Mexico	2010	110,000	250,000	188,100
Fryingpan-Arkansas, Colorado	1980		70,000	- 15,000
M&I Ruedi Reservoir, Colorado	2010		40,000	
Four County, Colorado	2010		40,000	- 4,000
San Miguel, Colorado	2010	26,000	85,000	70,460
Cheyenne, Wyoming	2010		31,000	- 10,000
West Divide, Colorado	2010	19,000	76,000	35,530
Animas-La Plata, Colorado-New Mexico	2010	47,500	146,000	81,225
Dolores, Colorado	2010	32,000	87,000	54,720
Dallas Creek, Colorado	2010	15,000	37,000	45,000
Resources Inc., Utah	2010		102,000	

Table 12. Contd. Future Water Resources Projects[a]

Project	Completion Date	Acreage	Total Flow (acre-feet)	Total Salt Load (tons)
LOWER COLORADO RIVER BASIN				
Arizona M&I, Arizona	1980		39,000	
Marble Canyon, Arizona	2010[b]		14,000	
Dixie Project, Utah	2010	11,615	62,000	14,000
Southern Nevada Pumping	2010		253,000	
Ft. Mohave Indian Reservation	1980	18,974	76,000	19,000
Chemeheuvi Indian Reservation	1980	1,900	8,000	2,000

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[a] Marble Canyon Project deleted from Bureau of Reclamation Progress Report No. 4 (Reference No. 28).

[b] References: U. S. Department of Interior, "Quality of Water, Colorado River Basin," Progress Report No. 3, January 1967 (Reference No. 29).

A different method was used to determine present and future water use in situations where groundwater is blended with Colorado River water to make up a given entity's supply. Since water demand is frequently a function of water quality, it was necessary to consider the demand for a blend of water with different qualities. If the entity in question was utilizing Colorado River water exclusively, the intake quality was taken as the quality of the Colorado River at the point of diversion. If, however, an entity utilized Colorado River water in conjunction with a groundwater supply and blended the two, it was necessary to estimate the intake quality by determining the quality of the resulting blended supply. The projected demand for water was then modified to reflect this quality.

Salt-Load Sources

Salt-load sources in the Upper Basin were estimated primarily from data contained in the Iorns report.(27) In cases where published information was lacking, the Project used its own supplemental data which was obtained from field surveys. A description of these surveys and results obtained are presented in Appendix A.

DETERMINATION OF WATER QUALITY

A computer program which calculates water quality at critical points in the system was used to integrate the hydrologic characteristics, water demand data, and estimates of salt loads for each target year. This program, a flow and salt-routing model, was used to develop estimates of the average mineral quality levels for the years 1960, 1980, and 2010.

The computer program simulates Basin response to input data in a series of calculations for small drainage areas. Figure 4 illustrates the method used for dividing the Basin into drainage areas and establishing

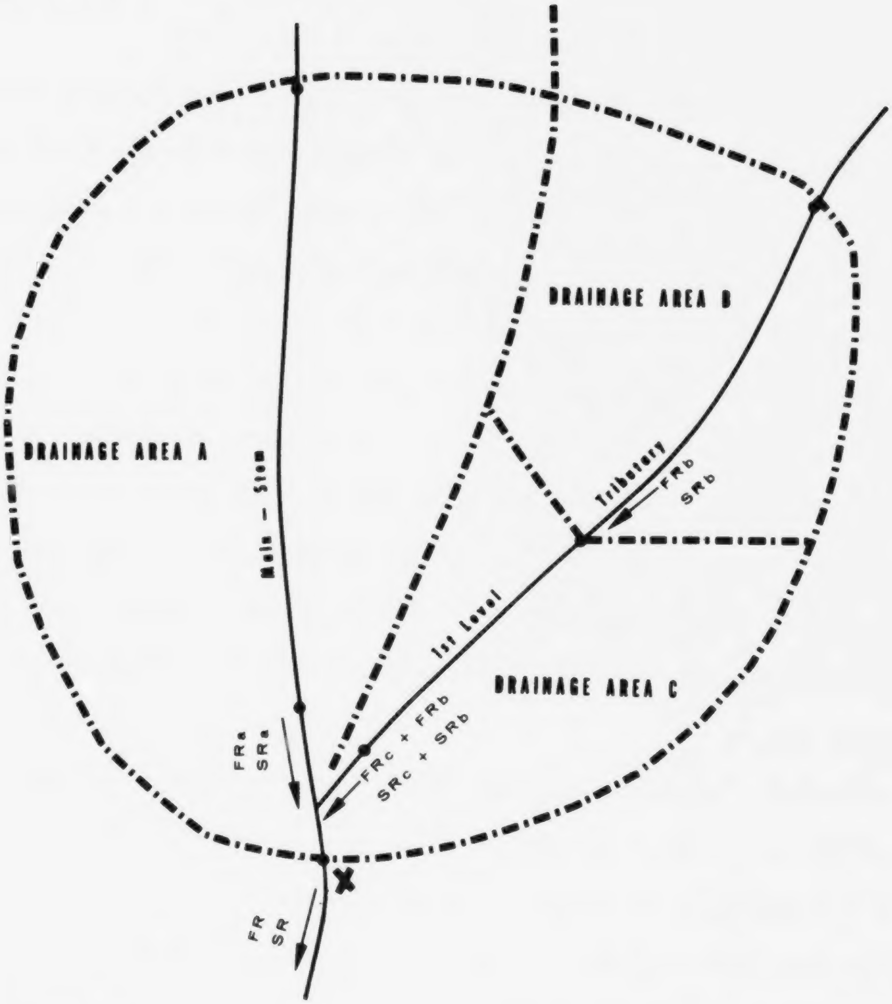

DRAINAGE AREA B
DRAINAGE AREA A
Main — Stem
Tributary
FRb
SRb
1st Level
DRAINAGE AREA C
FRa
SRa
FRc + FRb
SRc + SRb
FR
SR

Figure 4. Typical Drainage Area Used for Flow & Salt Routing Model for the Colorado River Basin

points at confluence of streams. Natural flow discharges and salt loads originating within the defined drainage areas were first determined. The effects of man's activities, such as depletions of water for consumptive use or addition of salt loads by irrigation, were added to the natural effects. The program then accumulates these effects and routes them downstream to be added to successive effects.

From Figure 4 the accumulated flow and salt load runoff below junction X would be $FR = FR_a + FR_b + FR_c$, and

$$SR = SR_a + SR_b + SR_c,$$ respectively.

The flow discharge runoff equation for each drainage area would be

$$FR_{a,b,c} = (AN \times CN) + DS - (IA \times CI) - (P \times CP) \pm DV;$$

and the salt load runoff equation would be

$$SR_{a,b,c} = (AN \times CN) + DS + (IA \times CI) + (P \times CP) \pm DV;$$

where $FR_{a,b,c}$ = annual flow runoff in acre-feet,

$SR_{a,b,c}$ = annual salt load runoff in tons,

AN = natural drainage area in square miles,

CN = coefficient for contributions from the natural area in acre-feet/sq. mi. or T/sq. mi.,

DS = annual contribution from discrete sources in acre-feet or tons,

IA = irrigated acreage,

CI = coefficient for depletions or contributions from irrigation in acre-feet/acre or tons/acre,

P = population,

CP = coefficient for depletions or contributions by the population in acre-feet/person or tons/person, and

DV = annual diversions (imports or exports) within the drainage area in acre-feet or tons.

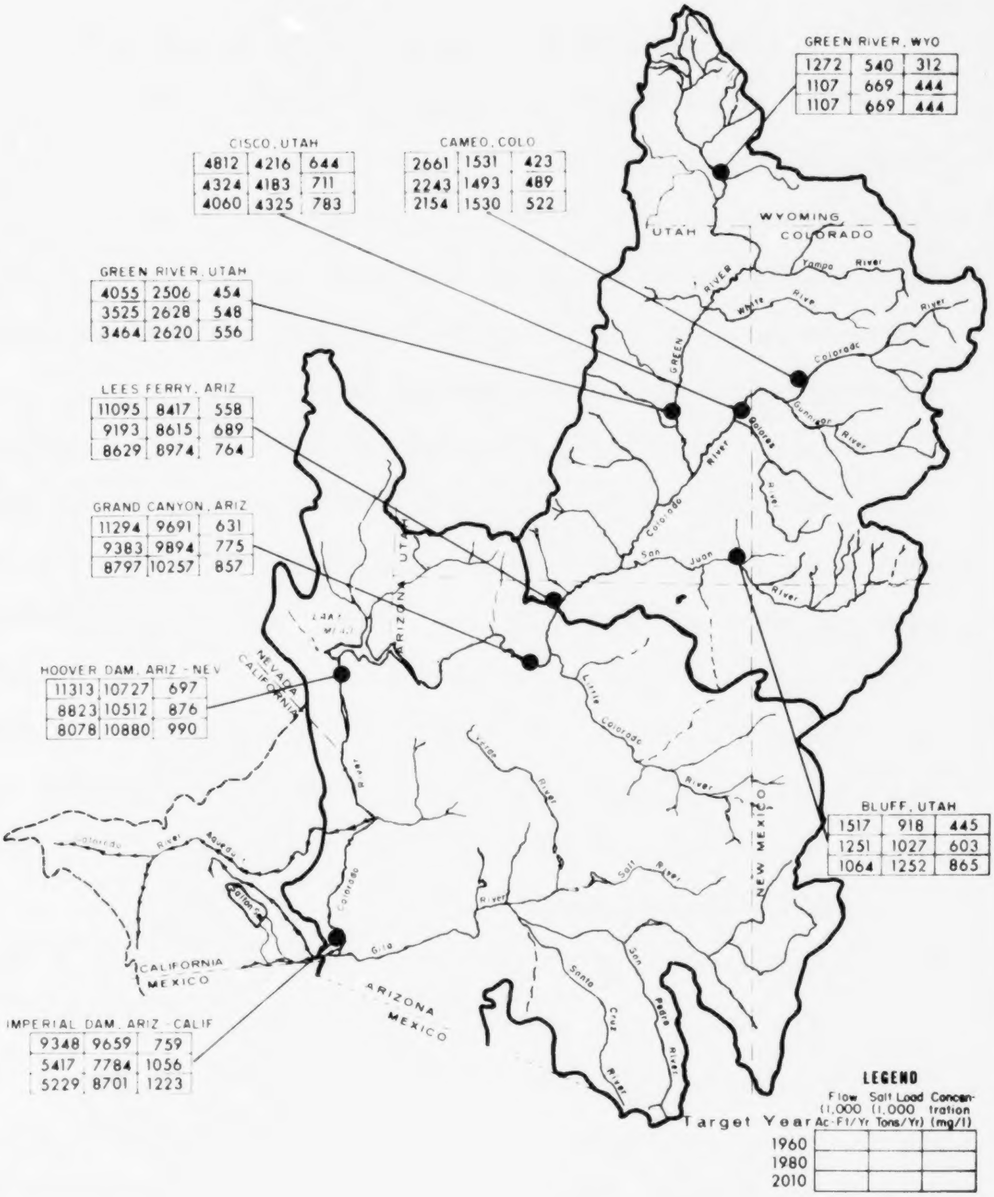
The drainage areas were divided, where possible, so that the stations or points selected for the routing model would coincide with the locations of USGS gaging stations. As the inflows of water in the Lower Basin were small compared to the Upper Basin, the routing model for the Lower Basin was simply a budget listing the various depletions of water.

TARGET YEAR MINERAL QUALITY

Flow depletions and expected salt loads from new irrigation projects, growth of existing irrigation district water demands, and increased municipal and industrial uses were projected independently and entered into the model. The model was used to correlate the data and to produce a new array of quality values for years 1980 and 2010. The water quality values obtained by this analysis are shown in Table 13 and Figure 5. Salinity concentrations were computed by the model to the nearest mg/l. This degree of refinement in reporting computer predictions was selected to allow evaluation of the small incremental changes in salinity concentrations produced by a given salt source or water resource development and to reduce rounding errors. It was not intended that a high degree of accuracy be implied as predictions of future salinity concentrations are dependent upon a number of factors which are not known with certainty.

Table 13. Water Quality Values (mg/l) for the Lower Main Stem Subbasin Obtained by Flow and Salt Routing Model for the Colorado River Basin

	1960		1980		2010	
Location	TDS	Hardness	TDS	Hardness	TDS	Hardness
Colorado River @ Hoover Dam	697	345	876	420	990	460
Colorado River @ Parker Dam	684	340	866	415	985	460
Colorado River @ Palo Verde	713	350	940	445	1082	495
Colorado River @ Imperial Dam	759	370	1056	485	1223	540


WYOMING
COLORADO
UTAH
ARIZONA
NEVADA
CALIFORNIA
NEW MEXICO
CALIFORNIA
MEXICO
ARIZONA
MEXICO
GREEN RIVER
Yampa River
White River
Colorado
Gunnison River
Dolores
Colorado River
San Juan River
Little Colorado River
Verde River
Salt River
Gila River
Santa Cruz River
San Pedro River
Colorado River Aqueduct
Salton Sea
LAKE MEAD
Colorado

GREEN RIVER, WYO

1272	540	312
1107	669	444
1107	669	444

CISCO, UTAH

4812	4216	644
4324	4183	711
4060	4325	783

CAMEO, COLO

2661	1531	423
2243	1493	489
2154	1530	522

GREEN RIVER, UTAH

4055	2506	454
3525	2628	548
3464	2620	556

LEES FERRY, ARIZ

11095	8417	558
9193	8615	689
8629	8974	764

GRAND CANYON, ARIZ

11294	9691	631
9383	9894	775
8797	10257	857

HOOVER DAM, ARIZ - NEV

11313	10727	697
8823	10512	876
8078	10880	990

BLUFF, UTAH

1517	918	445
1251	1027	603
1064	1252	865

IMPERIAL DAM, ARIZ - CALIF

9348	9659	759
5417	7784	1056
5229	8701	1223

LEGEND

Target Year	Flow (1,000 Ac-Ft/Yr	Salt Load (1,000 Tons/Yr)	Concentration (mg/l)
1960			
1980			
2010			

NOTE : Values shown are based on 1942 – 1961 period of record modified to 1960 conditions.

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SOUTHWEST REGION SAN FRANCISCO, CALIF.

Figure 5. Flow, Loads, & Salinity Concentrations in Streams in the Colorado River Basin

It is interesting to note that the quality at Lees Ferry is projected to increase from 558 mg/l to 764 mg/l (37 percent increase) while the quality at Imperial Dam, the last delivery point in the system, is projected to increase from 759 mg/l to 1223 mg/l (61 percent increase). These results tend to verify the conclusion that the impact of mineral quality degradation in the Colorado River Basin will be much more severe for downstream users than for upstream users.

The model describes the relative effect of the various types of salt sources on salinity concentrations. Accumulated data on flow, salt loading and salinity concentrations can be summarized by source for a number of key points in the system. Table 14 presents such a summary for the target year 1960 at Hoover Dam. As illustrated by the table, approximately 73 percent of the 1960 salinity concentration at Hoover Dam was contributed by various sources of salt loading and only 27 percent of the salinity was the result of consumptive water use including water exports from the basin.

From similar tables developed from routing model data, it is possible to determine the relative effect of projected changes on mineral quality. Future mineral quality changes at Hoover Dam due to projected consumptive use of water and added salt loads above that point are shown in Figure 6. It will be noted that nearly 83 percent of the projected mineral quality increase at Hoover Dam will be caused by increased consumptive use of water. Such a significant effect is important in view of anticipated diversions from the Upper Basin.

INDEX OF MINERAL QUALITY

For any given "steady state" of a river system, a fixed array of

Table 14. Effect of Various Factors on Salt Concentrations in Colorado River at Hoover Dam (1942-1961 period of record adjusted to 1960 conditions)a/

Factor	Flow (1000 AF/Yr)	Cumulative Flow (1000 AF/Yr)	Salt Load (1000 Tons/Yr)	Cumulative Salt Load (1000 Tons/Yr)	Cumulative Concentration		Change in Concentrationb/ Mg/l	Percent of Total Concentration
					Tons/AF	Mg/l		
Natural Diffuse Sources	14,471	14,471	5,408	5,408	0.374	275	275	39
Natural Point Sources	229	14,700	1,283	6,691	0.455	334	59	8
Irrigation (Salt Contribution)	0	14,700	3,536	10,227	0.696	512	178	26
Irrigation (Consumptive Use)	- 1,883	12,817	0	10,227	0.798	587	75	11
Municipal and Industrial Sources	- 42	12,775	146	10,373	0.812	597	10	1
Exports Out of Basin	- 465	12,310	- 37	10,336	0.840	617	20	3
Evaporation and Phreatophytes	- 1,409	10,901	0	10,336	0.948	697	80	12
Storage Release from Hoover	412	11,313	391	10,727	0.948	697	0	0
TOTAL		11,313		10,727		697		100

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a/ Based on data from the following sources:

(1) Iorns, W. V., Hembree, C. H., and Oakland, G. L., "1965 Water Resources of the Upper Colorado River Basin - Technical Reports," U. S. Geological Survey Professional Papers 441 and 442.

(2) U. S. Department of Interior, "Quality of Water, Colorado River Basin," Progress Report No. 3, January 1967.

(3) FWPCA unpublished records.

b/ Concentrations in this column will vary depending upon the order in which they are calculated.

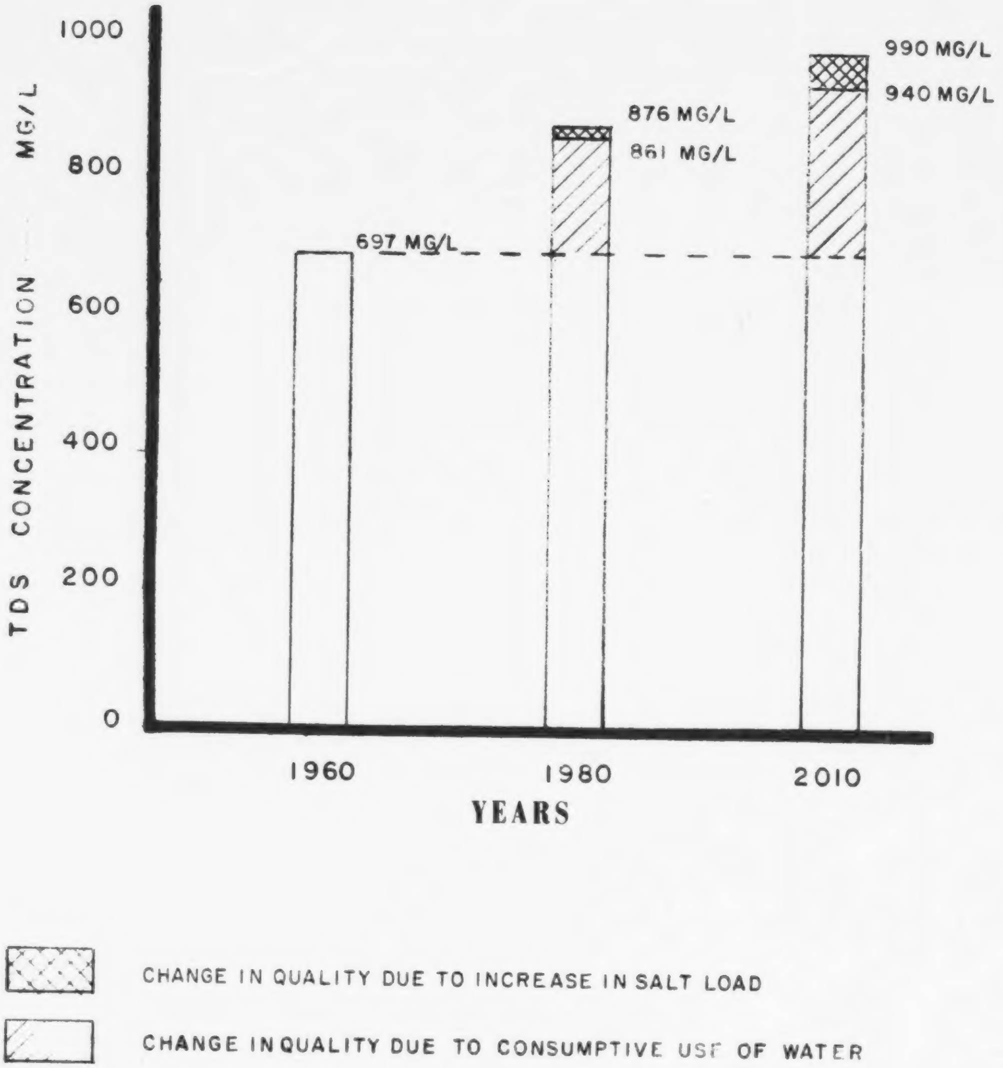


Figure 6. Future Mineral Quality Changes at Hoover Dam Due to Consumptive Use of Water & Salt Load Increases Above That Point

water quality and use data exists. A change in quality or use at any point may affect the entire system. To simplify presentation of the probable impact caused by a modification in the system, it is useful to have a single index representative of water quality for the entire system. Selection of such an index is discussed below.

Since the concentration and the volume of water withdrawn at each water-use location are important in determining total effects, one possible index representing the state of the system could be:

$$I = \sum_{i=1}^{n} D_i C_i \;/\; \sum_{i=1}^{n} D_i$$

Where: I is the mineral quality index,
D is the volume of diversion at a location,
C is the TDS concentration at a location,
i is a location index ranging from 1 to n, and
n is the total number of diversions in the basin.

A second, more simplified approach is to select a single key point in the system to which water quality at major points of use is related and utilize water quality at this key point as an index of the system. Essentially all of the economic impact of projected salinity increases will accrue to Lower Basin water users. Since Hoover Dam regulates water releases to Lower Basin users, salinity concentration at various downstream points of use can be directly related to salinity concentration at Hoover Dam. Therefore, mineral quality at Hoover Dam was selected as a simplified index of water quality for the entire Colorado Basin. For the remainder of this report, presentations of the economic impact of various proposed changes in water use are directly related to this mineral quality index at Hoover Dam.

CHAPTER IV. DIRECT PENALTY COST EVALUATION

DEFINITION OF PENALTY COST

In order to define the term "penalty cost," it is necessary to understand the term "detriments." Detriments are user costs incurred when a specific quality of water is used. A penalty cost is defined as the difference between the detriments associated with the use of two different levels of water quality; thus, it is based on similar economic conditions which permits the cost effect of water quality to be isolated. The following hypothetical situation will serve to illustrate the meaning of the terms defined above.

Assume that a city utilizing Colorado River water as its source of municipal supply has an intake hardness of 200 mg/l in 1960 and a forecasted intake hardness of 300 mg/l in 1980. The detriments in 1980 associated with using water of 200 mg/l and 300 mg/l hardness are shown as points "a" and "c" respectively in Figure 7. The difference between the detriments is the penalty cost "A" which would be incurred by the municipal users in 1980 if the hardness of their supply increasd from 200 mg/l to 300 mg/l. It should be noted that, if the intake quality remained at 200 mg/l from 1960 to 1980, there would be an increase in the detriments from 1960 to 1980 as indicated by points "a" and "d." The increase is caused by changes in economic conditions, such as a larger population affected, not by a change in the water quality. Although such a difference in detriments represents an economic penalty associated with water quality, it is not a penalty cost as defined above.

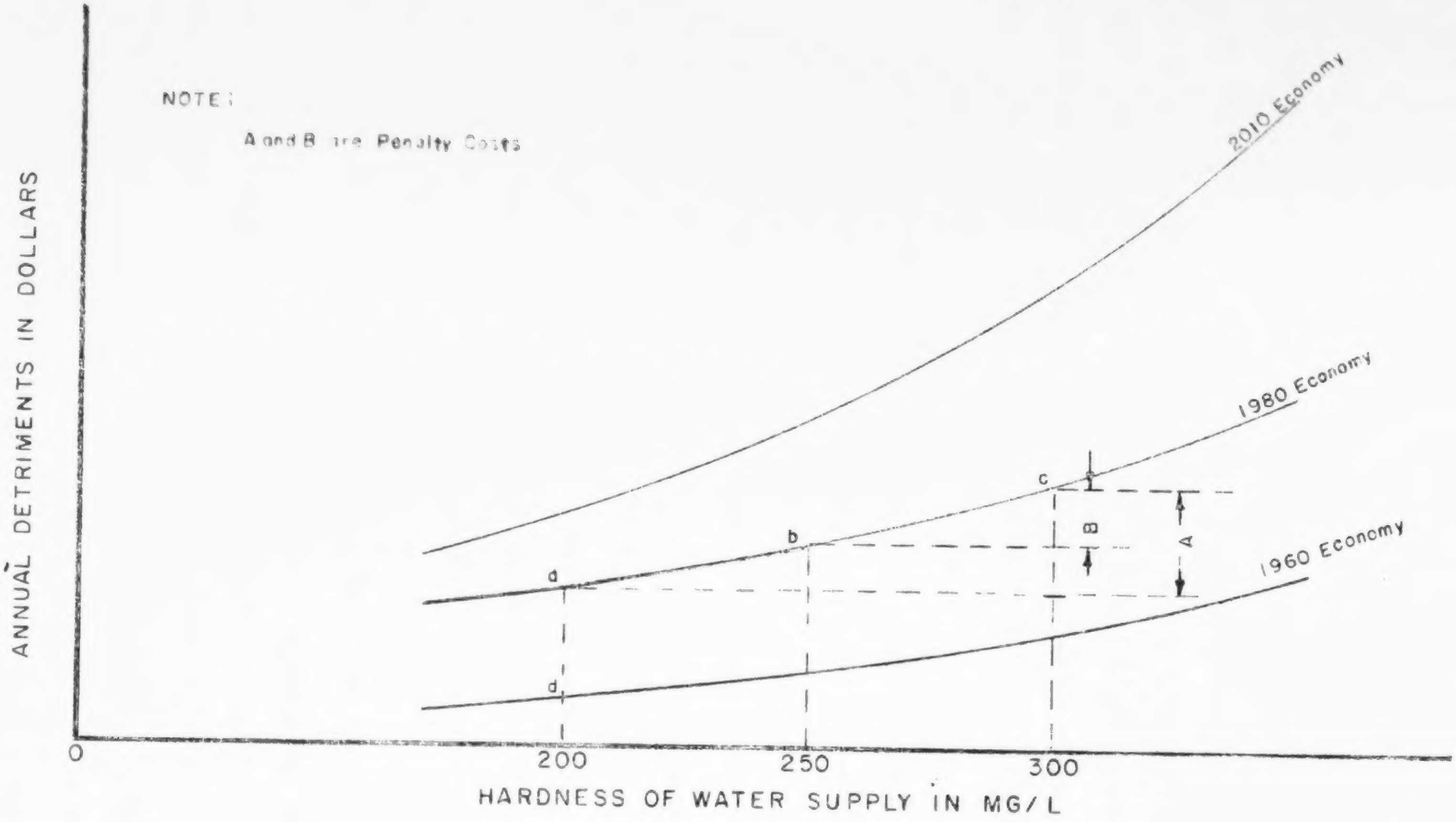


Figure 7. Illustration of Detriments & Penalty Costs Due to Water Quality Degradation

METHODS OF PENALTY COST EVALUATION

Users in the Lower Basin have recently begun to recognize that degradation of the mineral quality of Colorado River water is having a direct adverse affect upon their economic welfare. Although individual users have not felt the impact to a significant degree, there is a general awareness of the problem. In such a situation each individual affected begins searching for potential solutions which will offset the direct loss to his welfare. From various alternative solutions, the individual will generally select one which is the least costly.

In a similar fashion the Project attempted to formulate several alternatives for each major type of water use in the Basin, each of which was considered satisfactory from a practical viewpoint. Various alternatives were evaluated and one was selected for the purpose of analyzing basinwide effects. It should be emphasized that, even though one alternative was selected for use in the analysis, the Project does not propose that such an alternative be implemented in practice. This analysis was carried out for the purpose of measuring the value of anticipated changes in a physical system. The various alternatives considered and the one selected for use by the Project in its penalty-cost evaluations are discussed in considerable detail in the following sections.

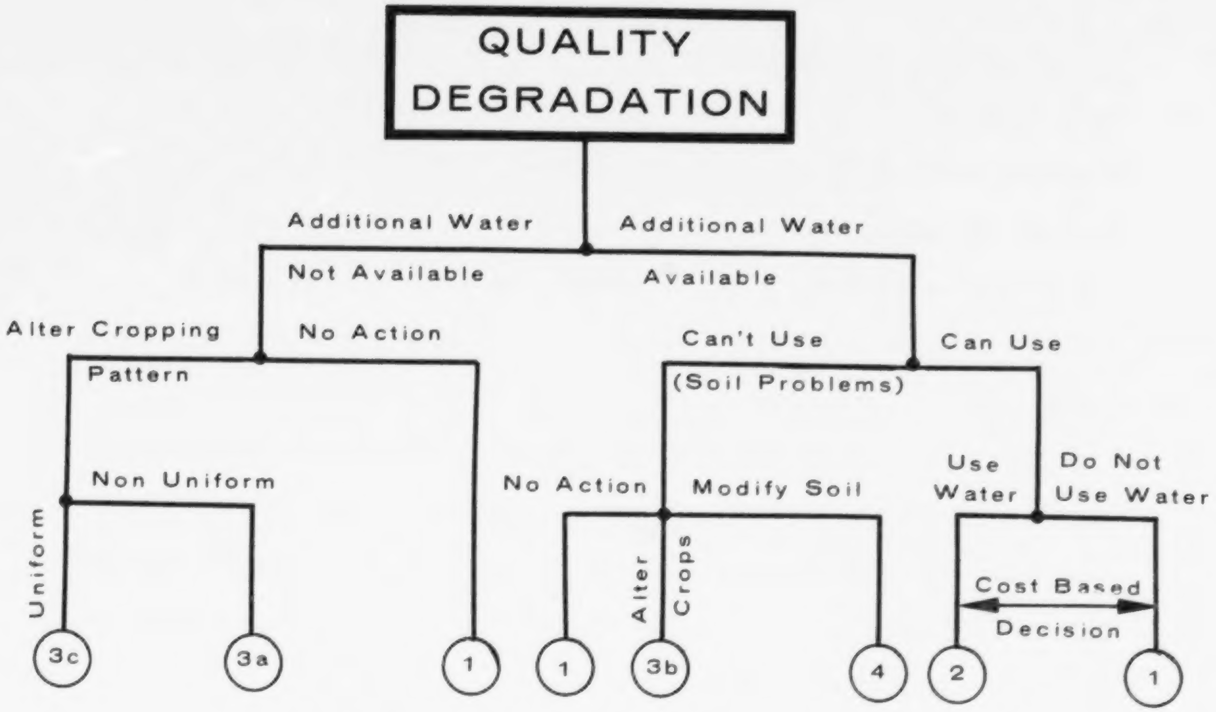
Irrigated Agriculture

Several alternatives are available to an irrigator when the quality of his water supply becomes degraded. If additional water is available and no soil problems exist, he can increase the quantity of applied leaching water. When soil conditions are such that additional leaching water cannot be applied, the alternatives are to adjust the soil conditions or replace salt-sensitive crops with less sensitive ones that require less leaching water. The remaining alternative with additional water available is to take no action and, thereby, suffer a decrease in crop yields. If additional water is not available, two alternatives exist. The acreage in production can be reduced, either uniformly or non-uniformly, or no action can be taken. All these alternatives are shown schematically in Figure 8.

The following methods were investigated: (1) the yield-decrement method, (2) the Scofield-Hill equivalent service concept,(30) (3) the "constant quality of percolate" leaching requirement formula,(9) (4) the uniform acreage reduction alternative, and (5) the selective acreage reduction alternative. The techniques for calculating penalty costs by each of these methods are discussed in the following sections.

Yield Decrement. One alternative available to an irrigator when the quality of his water supply becomes degraded is to take no remedial action. This is shown as alternative No. 1 in Figure 8. Salinity detriments in this case are considered to be the loss in yield per acre due to increased salinity in the irrigation water supply. The percent of optimum yields realized are calculated for base and for adjusted water qualities. The economic value of the difference in yield associated with the two water qualities represents the penalty costs due to increased salinity in the irrigation water.

The Department of Agriculture Salinity Laboratory at Riverside, California, has developed data(31) that show the relationship between the expected yield of various crops as a function of the root zone soil


QUALITY DEGRADATION
Additional Water Not Available
Additional Water Available
Alter Cropping Pattern
No Action
Can't Use (Soil Problems)
Can Use
Non Uniform
Uniform
No Action
Modify Soil
Alter Crops
Use Water
Do Not Use Water
Cost Based Decision
3c
3a
1
1
3b
4
2
1

ALTERNATIVE DIAGRAM

1. NO ACTION. LEADS TO YIELD REDUCTION.
2. INCREASE PURCHASE AND USE OF WATER.
3. MAINTAIN SAME TOTAL USE ON FEWER ACRES. LEADS TO MORE USE/ACRE.
    a. Remove Least Profitable Crops ($/A-ft.)
    b. Remove Least Tolerant Crops (Yield in $/ppm)
    c. Remove Crops in Proportion to Acreage
4. INCREASED PURCHASE OF SOIL CONDITIONERS.

Figure 8. Irrigation Water User Alternatives for Offsetting the Effects of Mineral Quality Degradation

saturation extract[1] quality. These data were used to construct salinity-yield curves for various crops as shown in Figure 9. The percent of optimum yield with respect to salinity can be computed by determining the mean conductivity of the root zone soil saturation extract and by reading the corresponding "percent of optimum yield" from the salinity crop yield curves. Since the consumptive use, amount of applied water, and quality of the irrigation water are known, the quality and quantity of the drainage water may be calculated using Department of Agriculture Handbook 60 formulas.[2] The mean conductivity of the root zone soil saturation extract is the average of the conductivities of the applied water and the drainage water. This average value is divided by two in order to correct the conductivity of the soil solution to an equivalent conductivity of the saturation extract, as recommended by the salinity laboratory.

As previously stated, the conductivity of the saturation extract, when applied to the empirical salinity-yield relationship, gives a percent of possible yield. In order to obtain the salinity detriments for each target year, including 1960, it was necessary to choose a base quality below the 1960 target-year quality. A base quality was selected for each area and was used in all calculations pertaining to that area.

1/ The electrical conductivity of the saturation extract of a soil was adopted by the salinity laboratory as a scale for estimating the salinity of a soil. The procedure for determining the saturation extract value involves preparing a saturated soil paste by stirring, during the addition of distilled water, until a characteristic end-point is reached. A suction filter is then used to obtain a sufficient amount of the extract for making the conductivity measurement.

2/ U. S. Department of Agriculture, U. S. Salinity Laboratory, "Saline and Alkali Soils," Agriculture Handbook No. 60, 1954, pp. 31-38. (Reference No. 10).

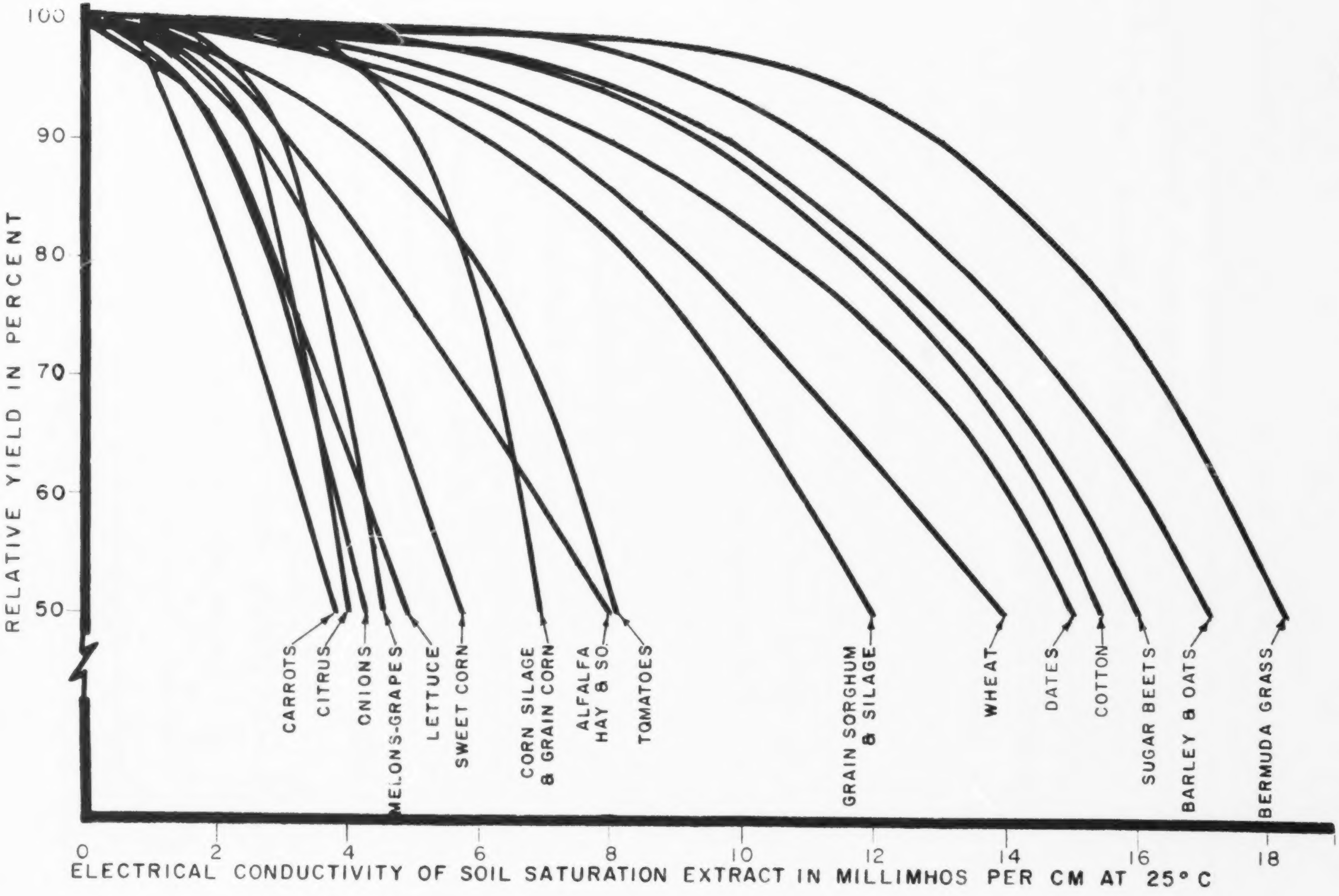


Figure 9. Salt Tolerance of Major Crops Grown in Study Areas

The salinity detriment for each crop is equal to the decrease in yield per acre times the total gross value of the crop, and is calculated according to the following equation:

$$DET_{YD} = \left(1 - \frac{PYIELD_2}{PYIELD_1}\right)(A)(V) \; ;$$

where: DET_{YD} = Yield decrement detriment for a crop in a given area for a given quality (TDS),

$PYIELD_1$ = Percent of optimum yield at base quality,

$PYIELD_2$ = Percent of optimum yield at adjusted quality (target year),

A = Gross acreage of the crop, and

V = Gross value of crop per acre.

Gross value is used here because the technique assumes no change in farm management practices. Therefore, pre-harvest costs are still incurred, and no profit is realized for that portion of the crop lost because of quality degradation. To obtain the total detriments for each area for a given target year, the detriments for all the crops are summed. The penalty costs for 1980 and 2010 are the differences between the detriments for these two years, respectively, and the 1960 detriments. It should be noted that the actual values of the detriments have little meaning because a base quality was used to obtain them. However, the penalty costs do have meaning if the same base quality is used for all target year calculations.

Equivalent Service. As an alternative to the no-action condition, the irrigator could choose to maintain existing yields as the quality of his water supply degrades. This is shown as alternative No. 2 in Figure 8. He could accomplish this by applying more water in order to increase the leaching fraction. In this case the major problem lies in determining how much additional water would be required. Hill and Scofield considered this problem and set forth the concept of "equivalent service"(30) as one method of calculating the amount of water required. Equivalent service requires reduction in the concentration of the drainage water in order to offset the increase in concentration of dissolved solids in the applied water. This concept calls for a substantial increase in the leaching fraction in order to improve the drainage water quality.

The quantity of water required for a given crop being irrigated with a certain quality of water can be calculated by the following equation:

$$D_a = D_o \left(\frac{4Cr - 3Ca}{4Cr - 4Ca} \right) A;$$

where:

D_a = Quantity of applied water required for a crop at a given quality,

D_o = Consumptive use required by a crop,

Ca = Concentration of salts in applied water,

Cr = Average effective concentration of the soil solution, and

A = Gross acreage of crop.

As was the case with the yield decrement method, it is felt that the mean effective concentration of the soil extract is closer to one-fourth of the sum of the concentrations of the applied water and the percolate. It should be noted that this judgment leads to a more conservative estimate of penalty costs than that resulting from using the average of the concentration of the applied water and the percolate.

Maintaining the root zone water quality at its present level would be sufficient to maintain existing crop yields. However, in order to evaluate penalty costs attributable to this alternative, the volume of additional water needed to maintain present root zone quality has to be determined for the range of irrigation water quality expected in the future. It should be noted that maintenance of present root zone concentrations requires use of water in excess of the amount required to maintain salt balance.

The dollar value of salinity detriments in a given area is calculated by the following equation:

$$\text{TOTAL DET}_{ES} = \left(\frac{\Sigma D_{a2} - \Sigma D_{a1}}{E}\right)(RV_w);$$

where: TOTAL DET_{ES} = Total equivalent service detriments for a given area at adjusted quality,

ΣD_{a2} = Summation of applied water required for all crops at adjusted quality (target year),

ΣD_{a1} = Summation of applied water required for all crops at base quality,

RV_w = Residual value of water, and

E = Overall delivery efficiency.

The penalty costs for 1980 and 2010 are the difference between the detriments for these two years, respectively, and the 1960 detriments.

A short discussion is in order at this point concerning the economic value of water used for irrigation. Water for irrigating agricultural crops is often in scarce supply, thus it has an economic value. Several methods may be used in determining the value of irrigation water. The most widely accepted method is the "market price," where water is not appurtenant to the land. Very few areas have a true market price for water, i.e., where water is traded or rented for the season just like any other commodity. In the absence of a market price for irrigation water in the Colorado River Basin, the "residual value" is the most widely accepted substitute. The residual value of irrigation water represents the average amount a farmer can pay for water without impinging on the going rate of return to other inputs (land, labor, capital, overhead, and management) used in crop production. Crop budgets were used to calculate crop receipts, crop expenses, and the return to water. Total residual value for each crop and residual value per acre-foot of water applied were both calculated.

When the TDS concentration of the applied water equals the present mean root zone quality for any crop, no amount of water of the same quality can dilute it enough to offset the concentrating effect caused by consumptive use and the technique of equivalent service is no longer applicable. Therefore, salinity detriments calculated in this manner become infinitely large when the quality of water nears the present mean root zone quality of the most inefficiently irrigated crop.

Since excess amounts of water are applied in some areas and the supply of water is limited in others, equivalent service has been found to be not directly applicable to areas in the Lower Colorado River region.[1]

Constant Quality of Percolate. The equivalent service concept discussed in the previous section is one method of calculating leaching water requirements. Another method is known as the "constant quality of percolate." The theories used as a basis for this method are described in detail in Handbook 60 published by the U. S. Department of Agriculture.(10) The equation developed for calculating the leaching water requirement for a given applied water quality and for a particular crop is:

$$LR = \frac{TOL}{TOL - QUAL}(U)(A) ;$$

where:

LR = Total leaching requirement for a crop at a given quality,

TOL = Salt tolerance of crop in mmhos/cm,[2]

$QUAL$ = Quality of irrigation water in mmhos/cm,

U = Consumptive use (evapotranspiration), and

A = Gross acreage of crop.

Total detriments for a given area are calculated according to the following equation:

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[1] The staff of the Economic Research Service, USDA, collaborated in the investigations; results were also reviewed with Dr. Bernstein and the staff of the salinity laboratory, as well as Dr. Vaughn Hansen and Mr. Raymond Hill who served as consultants to the Project.

[2] According to Mr. L. V. Wilcox, the conductivity of the drainage water associated with a 50 percent decrease in yield is nearly the same as the conductivity of the root zone saturation extract associated with a 10 percent reduction in yield.

$$\text{TOTAL DET}_{CQP} = \frac{(\Sigma LR_2 - \Sigma LR_1)}{E} (RV_w) ;$$

where: TOTAL DET_{CQP} = Total detriments for a given area at adjusted quality for target year,

ΣLR_2 = Summation of leaching water requirements for all crops at adjusted quality for target year,

ΣLR_1 = Summation of leaching water requirements for all crops at base quality,

RV_w = Residual value of water, and

E = Overall delivery efficiency.

The penalty costs for 1980 and 2010 are the differences between the detriments for these two years, respectively, and the 1960 detriments.

To determine the penalty costs associated with quality degradation, it is necessary to account for the increase in conveyance losses and to determine the dollar value of this quantity of water. This is done by dividing the increase in leaching water by the overall delivery efficiency.1/ The costs added by the need for extra labor, more fertilizer, and additional drainage associated with the application of more irrigation water should be added to these detriments. The latter has been shown to be quite substantial, sometimes equal to the value of the water itself.

In many locations waters of the Colorado River are fully appropriated or systems are used to capacity. In such cases an irrigator may be unable to purchase more water at a reasonable cost. He does have the option, however, of reallocating the priorities of use without

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1/ This includes conveyance, main system, and farm lateral losses.

increasing total consumption. In evaluating the costs of this option, the water requirement is determined as explained above except it is assumed that the additional water would be available from a reduction in irrigated acreage. Thus, slightly less additional water is required in this case since quality control water is not needed on the acreage taken out of production. The methods used in the acreage reduction analyses are described in the following sections.

Uniform Acreage Reduction. In the event additional water is not available for leaching as the quality degrades, an irrigator may take a portion of his crop land out of production and use the water thereby saved to increase the amount of leaching water applied to the remaining crop acreage. Even though this may prevent any yield reduction of the remaining crops, the profit that would have been made on the crops taken out of production is lost. Three methods of reducing acreage were investigated: (1) removal of a portion of all crops in proportion to total acreage (uniform reduction), (2) removal of the least profitable crops, and (3) removal of the least salt-tolerant crops. These alternatives are shown as "3c," "3a," and "3b" respectively in Figure 8.

The first step in determining detriments by the uniform acreage reduction technique is to calculate the leaching water requirements associated with a base quality and an adjusted quality for the target year. The "constant quality of percolate" method is used to obtain these leaching water quantities. The next step is to calculate the total volume of water required at the adjusted quality using the following equation:

$$R_2 = \sum_{i=1}^{n} \left(\frac{CU}{EFF} + LR_2 \right) ;$$

where: R_2 = Total volume of water required at adjusted quality,

CU = Total consumptive use (evapotranspiration) of the i^{th} crop,

EFF = Field efficiency, and

LR_2 = Total leaching requirement for the i^{th} crop at adjusted water quality.

To obtain the percentage of land to be removed, let

$$P = \frac{\Delta LR}{R_2} \quad (100\%) ;$$

P = Percent of land to be removed from production, and

ΔLR = Additional leaching requirement, ($\Sigma LR_2 - \Sigma LR_1$), associated with quality degradation.

Careful analysis reveals that the percentage, "P" determined by the above equation is slightly over-estimated since no additional leaching water is needed on the land removed from production. To obtain the actual percent of land to be removed, it is necessary to use a successive approximation technique.

First, the true quantity of additional leaching water, LR', needed on the acreage that remains is calculated by the following equation:

$$\Delta LR' = PR_2 - P^2R_2 + P^3R_2 - P^4R_2 + \ldots + P^nR_2.$$

The actual or true percent to be removed, P', is then equal to $\frac{\Delta LR'}{R_2}$. By substitution, the following equation can be derived:

$$P'R_2 = PR_2 - P^2R_2 + P^3R_2 - P^4R_2 + \ldots + P^nR_2 ,$$

and

$$P' = P - P^2 + P^3 - P^4 + \ldots + P^n .$$

If P is less than 100%, which it will be, the sum of the infinite series can be expressed as $P' = \frac{P}{1 + P}$. After P' is determined, the total salinity detriments can be calculated by the following equation:

$$\text{TOTAL DET}_{\text{UAR}} = \sum_{i=1}^{n} (A_i V_i P') ;$$

where: $\text{TOTAL DET}_{\text{UAR}}$ = Total uniform acreage reduction detriments for a given area at adjusted quality,

A_i = Gross acreage of i^{th} crop before reduction, and

V_i = Net value of i^{th} crop.

The net value is used because production costs are not incurred and only profit is lost.

Selective Acreage Reduction. Another acreage reduction method involves taking out of production the least profitable crops. The first step in this method is to calculate the leaching water requirements associated with a base quality and the adjusted quality for the target year by the "constant quality of percolate" method. The additional leaching requirement, ΔLR, due to quality degradation is the difference in the leaching water requirements referred to in the previous section. The quantity, ΔLR, is the amount of water that would be saved by reducing the acreage. The next step is to arrange the crops in order of increasing economic return from water use and then to calculate the total amount of water required by each crop according to the following equation:

$$r_2 = \left(\frac{CU}{EFF} + LR_2\right) ;$$

where: r_2 = Total water required by the i^{th} crop,

CU = Total consumptive use (evapotranspiration) of the i^{th} crop,

EFF = Field efficiency,

LR_2 = Total leaching requirement of the i^{th} crop at adjusted quality.

The next step in the analysis is to determine if the total amount of water required by the least profitable crop is less than ΔLR. If it is, the entire crop is removed from production and ΔLR is reduced by r_2 of the crop removed. The same comparison is then made between the amount of ΔLR remaining and the total amount of water required by the next lowest profitable crop. If the r_2 of this crop is less than the portion of ΔLR remaining, the entire crop is removed and the process is repeated.

At some point in the process, the portion of ΔLR remaining after several crops have been removed will be less than the total amount of water required by the next crop in line for removal. (Actually this could be the case with the least profitable crop grown, or the first considered.) When this point in the process is reached, it becomes necessary to determine the portion of this crop to be removed. The actual percentage of the crop to be removed, F, is equal to $\frac{D}{1 + D}$ (100 percent). The value of D is determined by dividing the portion of ΔLR

remaining at this stage by r_2 of the crop being considered. At this point, the analysis becomes identical to the uniform acreage reduction technique. The values D and F are similar to the values P and P', respectively.

After F is determined, the total salinity detriments can be determined by the following equation:

$$\text{TOTAL DET}_{SAR} = \sum_{i=o}^{i=x-1} (A_i V_i) + A_x V_x F \;;$$

TOTAL DET_{SAR} = Total selective acreage reduction detriments for a given area at adjusted quality,

A_o = 0,

X = Reference number of the last crop affected (the numbering system begins with the least profitable and proceeds to the most profitable),

A_i = Gross acreage of the i^{th} crop,

V_i = Net value of the i^{th} crop,

A_x = Gross acreage of the i=x crop, and

V_x = Net value of the i=x crop.

A third acreage reduction method, which involves selective removal of those crops having the greatest yield loss per unit of root zone concentration increase, was not used by the Project.

Labor, Fertilizer, and Drainage. When more irrigation water is applied, additional labor costs are incurred; additional amounts of fertilizer are lost; and additional drainage facilities may be needed. In the case of additional labor costs it was assumed that irrigators would tend to decrease the interval between irrigations. In order to maximize the interval, an irrigator would apply the maximum amount of water which could be beneficially used during each irrigation. It follows that any substantial increased water requirement would necessitate more irrigations per year. The cost of additional irrigations was assessed at $2 per foot of required additional irrigation water in excess of three inches. The initial three inches of additional water was assessed no labor cost. The foregoing values are based on an application of six inches per irrigation at a cost of approximately $1 per irrigation.

Fertilizer losses were calculated according to a first-order chemical solution reaction equation. For convenience, this equation was expressed in the form:

$$L = L_o P^n ;$$

where: L_o = Quantity of fertilizer presently applied,

L = Quantity of fertilizer remaining,

P = Percent of fertilizer remaining under present conditions, and

n = Ratio of the volume of drainage with degraded water supply to present volume of drainage.

From this equation, the loss in nitrogen fertilizer associated with increases in drainage water may be calculated. This amount is multiplied by the 1960 fertilizer cost to establish a dollar penalty cost ($.12/lb.).

Drainage facilities were assessed no penalty costs for two reasons. First, it was found that irrigation districts build facilities as they are needed; and secondly, the additional leaching water required because of water quality degradation can easily be carried by the existing closed drain systems. Hence, the size of drains would not have to be increased due to additional volumes of percolating water.

Selection of Best Method. Penalty costs associated with each of the alternatives discussed above were calculated for each of the major irrigation water-use areas below Hoover Dam, and the results compared. Figure 10 shows such a comparison for a typical water-use area.

Within each of the study areas, water users utilize various combinations of alternatives in an attempt to minimize the economic impact of salinity increases in their water supply. Given sufficient data with regard to the acreage and crops to which each alternative is applied, it would be possible to accurately evaluate the magnitude of present salinity detriments. However, such data is not available. Also, the accuracy of projections of future detriments based on present combinations of alternatives would be questionable as changing conditions might alter the selection of alternatives in the future. It was thus desirable to select one alternative as a means of evaluating present and future penalty costs. The selective acreage reduction method, the least cost alternative, produced inconsistent results and was rejected. The yield decrement method, which assumes no increased use of water nor any acreage reduction, was selected as it was considered to be most applicable to conditions in the three study areas. This method results in a conservative estimate of penalty costs since any combination of other methods would result in higher costs. Thus, present penalty costs are probably higher than estimates presented in this report, but a more accurate evaluation cannot be made at this time.

Industrial

The study of industrial penalty costs of mineralized water supplies

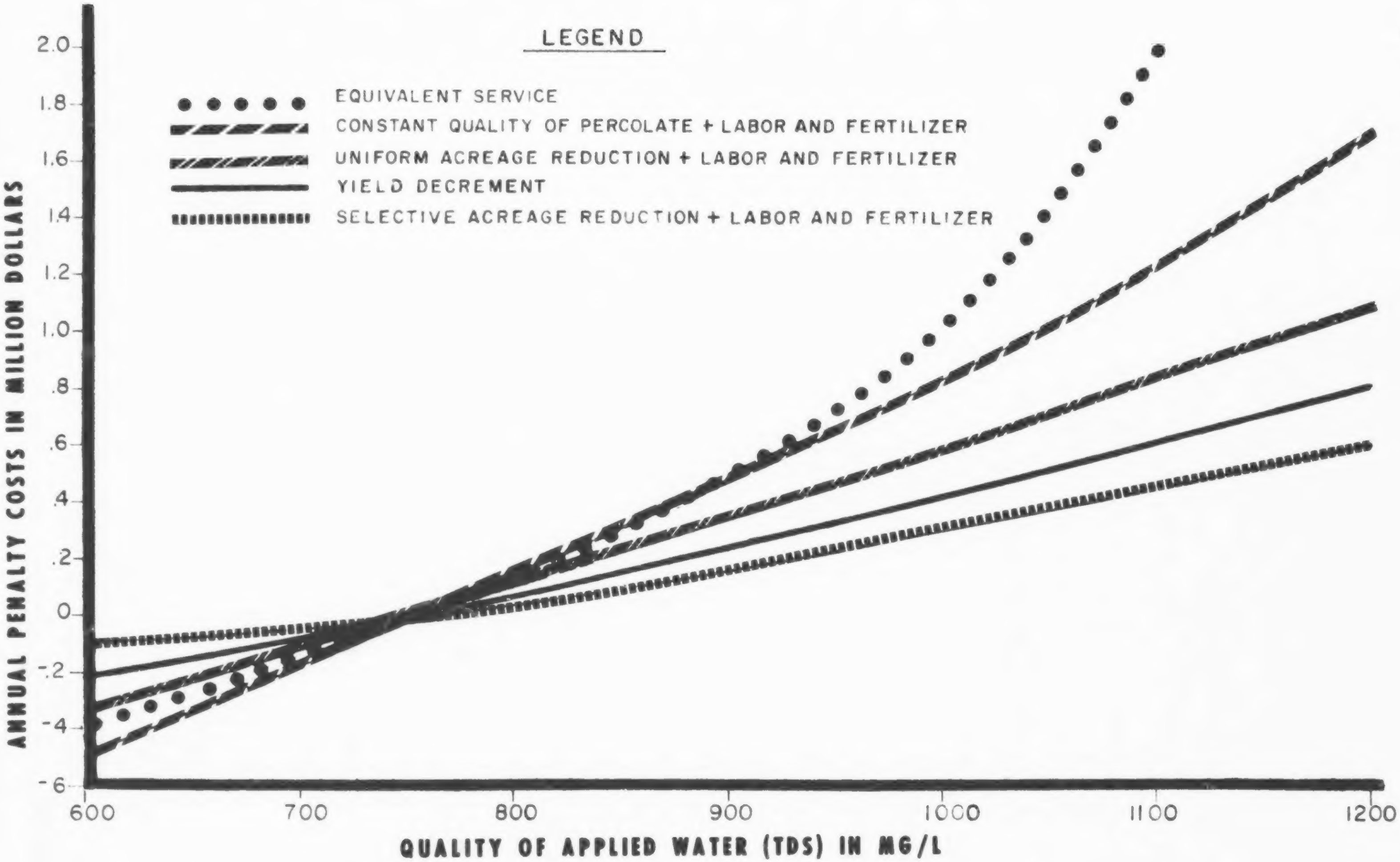

Figure 10. Comparative Results of Irrigated Agriculture Penalty Cost for a Portion of Yuma County - 1960

involves two of the four major types of industrial uses classified in Chapter II, namely cooling and boiler feed. The large number and variety of manufacturing industries in the major centers of water use, especially in Southern California,[1] made it impracticable to attempt an evaluation of effects on process waters within the scope of this study. In addition, process water use falls into two categories: (1) use that is insensitive to small incremental changes in mineral concentration, or (2) use that requires a completely demineralized supply. In either case the effect of changes in mineral quality over the range of concentrations expected to prevail is considered to be unmeasurable. General purpose water, or that used for plant drinking water, sanitation, lawn irrigation, and fire protection, is small in volume compared with other types; and for some applications, such as general cleaning and fire protection, the mineral content is not very important.

In view of these considerations, the industrial penalty costs derived in the Project's study are somewhat understated. There is no doubt, however, that the included costs cover a major portion of the fresh water used in manufacturing. In the United States as a whole over 74 percent of all industrial fresh water is used in cooling and boiler feed,(33) and in the state of California 67 percent is so employed.(34) A survey of water use in the chemical and metallurgical complex at Henderson, Nevada, made in August, 1964, by the Nevada Department of Public Health(35) showed 80 percent of the water to be employed for cooling, four percent for boiler feed, and the remaining 16 percent for processing, sanitary, and miscellaneous purposes.

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[1] Bureau of the Census, "Statistical Abstract of the United States," 1964, lists 17,665 manufacturing plants in the Los Angeles-San Diego metropolitan areas. (Reference No. 32).

There are two pertinent types of cooling and boiler systems: those which are not sensitive to mineral quality and those which are sensitive to mineral quality. High-pressure boilers require a demineralized supply; thus, they are not sensitive to minor changes in plant intake water quality. Similarly, specially designed cooling towers can accept brackish or highly saline waters; thus, they are insensitive to water quality.

Low-pressure boilers and cooling towers on fresh water systems, however, can tolerate only a limited concentration of dissolved mineral constituents. These systems, therefore, are directly affected by changes in mineral quality. This analysis is based entirely on an evaluation of penalty costs associated with Colorado River water used in sensitive systems. Therefore, all references to cooling and boiler feed water are meant to imply such use in sensitive systems only.

Current practice in the region has established the tolerance limit for low-pressure boilers to be in the range of 2,000 to 3,500 mg/1 of TDS. There are several suggested requirements for mineral quality limits of boiler feed supply water which depend on the operating pressure of the boiler system.(6, 36) (See Table 1 in Chapter II.) Limited investigations of manufacturing plant practice made in the Colorado River Basin indicated that steam for plant processes is generated at comparatively low pressure, 300 psi and under. This is in contrast with operation of modern thermoelectric power stations where very high pressures are often employed. Accordingly, the value of 3,500 mg/1 was used in the Project's study as a basis for the determination of penalty effects of saline boiler feed water.

For the Colorado River Basin, it appears that upper limits of dissolved solids for cooling water supplies are somewhat lower than for boiler feed water supplies. The limited studies which the Project was able to make indicate that the maximum in actual practice ranges from 1,000 mg/l to 2,500 mg/l. Accordingly, a value of 2,000 mg/l seems typical and was used as a basis for penalty cost assessment.

To simplify the calculation of industrial penalty costs, a single tolerance value was established for a system which considered both boiler feed and cooling use. It was found that cooling water use accounted for at least seven times the boiler feed usage (Table 15); and, based on this information, a volume-weighted tolerance was calculated to be approximately 2,200 mg/l.

Material balance in these systems establishes the quantity of discharge water required for any level of water use, intake quality, and system tolerance. Increasing concentrations of dissolved mineral constituents in the feed water necessitates an increase in the discharge requirement, and thus an increase in the water intake requirement, in order to prevent salt accumulation within the system. The increase in water use, the 1960 cost of water, and feed-water treatment costs were used in the assessment of industrial penalty costs.

The cleaning and sanitary water use portions of the industrial supply were assessed no user penalty costs. Only those costs incurred in providing and treating additional makeup water for cooling and low-pressure boiler systems were used in assessing industrial penalty costs.

Four major steps were required to evaluate industrial penalty

Table 15. Annual Manufacturing Water Requirement by Type of Use in California 1957-59

SIC Code	Type of Industry	Total Intake Acre-Feet	Cooling		Processing		Boiler Feed		Sanitary & Misc.	
			Acre-Feet	% of Total	Acre-Feet	% of Total	Acre-Feet	% of Total	Acre-Feet	% of Total
290	Petroleum Refining	148,000	128,500	86.9	3,850	2.6	13,490	9.1	2,070	1.4
200	Food	93,600	44,800	47.8	30,900	33.0	4,680	5.0	13,500	14.4
280	Chemical & Allied Products	60,600	31,300	51.6	21,000	34.7	5,340	8.8	3,090	5.1
260	Paper & Allied Products	24,200	6,500	26.8	16,250	67.0	655	2.7	849	3.5
320	Stone, Clay & Glass	27,900	11,000	39.3	14,700	52.6	559	2.0	1,680	6.0
340	Fabricated Metal Products	5,070	665	13.1	3,070	60.6	137	2.7	1,190	23.5
370	Transportation Equipment	12,600	1,110	8.8	5,460	43.4	302	2.4	5,710	45.4
330	Primary Metals	9,890	4,400	44.3	1,580	16.0	1,220	12.3	2,620	26.5
240	Lumber (wood except furniture)	27,100	10,850	40.1	4,070	15.0	10,050	37.1	2,080	7.7
	Sub-Totals	408,960	239,125		100,880		36,433		32,789	
	Percent of Total	-- 100.0	--	58.5	--	24.6	--	8.9	--	8.0
	Total for all Manufactures	421,700	242,500		104,100		37,100		37,900	
	Percent of Total	100.0	--	57.5	--	24.7	--	8.8	--	9.0

costs: (1) present and future intake water demands for the cooling and boiler feed water categories of use were estimated; (2) the quality of available supplies, including the effect of blending different supplies, was determined; (3) the required increase in water intake to offset quality degradation was calculated; and (4) the penalty costs associated with quality degradation were derived. Methodology used in the penalty cost assessment varied slightly between the study areas, but the basic four-step approach was used in all. A discussion of each step, with an explanation of the differences in methodology used for specific areas, is presented in the following sections.

Intake Water Requirements. Intake water requirements were estimated by the input-output model (see Chapter V) method in the Lower Main Stem study area and by trend-extrapolation methods in the Southern California study area. As explained in the section entitled, "Determination of Direct Penalty Costs, Gila Study Area," it was determined that industrial user penalty costs could not be calculated for the Gila study area.

Cooling and boiler feed intake water requirements for each economic sector of an input-output table can be calculated by the following equation:

$$U = (TGO)(W_i)(\%) / 325851 ;$$

where: U = Cooling and boiler feed use in acre-feet,

TGO = Total gross output in \$,

W_i = Water use coefficient in gal/\$, and

$\%$ = Percent of total use for cooling and boiler feed purposes.

As previously noted, this relationship was used for industries located in the Lower Main Stem study area because an extensive study of the subbasin economy had been completed and the input-output, or transactions, table had been assembled.

At the time of this phase of the Project's study, the input-output table had not been constructed for the Southern California area; therefore, more conventional techniques of trend-extrapolation were used for Southern California. Such techniques are well known and will not be discussed here. The data and assumptions which were utilized are discussed in the last section of this chapter.

Quality of Supply. As described in Chapter III, the mineral quality of the Colorado River was determined by a computer program at critical points throughout the Basin for each of the target years. No additional calculations were required for those industries served directly from the river.

Some industries were known to rely on a blended water supply from the Colorado River and one or more other sources. The determination of the blended quality in such situations is straightforward once the volume and quality of each source have been established. For a three-source blended supply,

$$q_b = \frac{(q_1)(F_1) + (q_2)(F_2) + (q_3)(F_3)}{F_1 + F_2 + F_3}$$

where: q_b = quality of the blended supply,

q_1, q_2, q_3 = mineral qualities of each source

F_1, F_2, F_3 = volumes of water from each source used in the blended supply.

Many assumptions must be made to determine the quality of a blended supply. A discussion of assumptions made and the resulting qualities appear in the last section of this chapter entitled, "Determination of Direct Penalty Costs."

Incremental Water Requirement. A mathematical relationship, derived from salt-balance and water-balance equations for a closed system, was used to determine the amount of additional water required to offset any increase in dissolved solids projected for each supply. The relationship is:

$$\Delta I = U\left[\frac{T\,(Q_2 - Q_1)}{(T - Q_2)\,(T - Q_1)}\right]$$

where: ΔI = Change in intake volume in acre-feet resulting from the change in quality from Q_1 to Q_2,

U = Cooling and boiler feed water use in acre-feet,

T = Tolerance of system in mg/l or tons/acre-foot, and

Q_2, Q_1 = Quality of intake in mg/l or tons/acre-foot.

Penalty Cost Assessment. The difference in makeup water requirements at any two levels of quality, multiplied by the unit cost of water, equals the first detriment associated with a change in water quality. Since the additional makeup water needs to be chemically treated in the same manner as the rest, a second detriment is computed by multiplying the incremental amount of makeup water by its unit cost of treatment. Costs of treating cooling water vary according to the type of treatment, scale of the operation, and local costs of chemicals.

Municipal

Although irrigation is the major water use in the Basin, municipal use is also significant. Hardness, which is closely correlated with dissolved solids content, creates undesirable effects in domestic uses. Three alternative methods of evaluating the economic impact upon municipal uses were examined: (1) the acceptance of undesirable effects, (2) home water softening, and (3) central softening. Each of these methods is discussed in the following section.

Acceptance of Undesirable Effects. Domestic users may elect to accept the consequences of a degraded water supply, in which case the economic penalties associated with soap use, corrosion, and evaporative cooling systems are incurred. However, only the additional soap costs were used in evaluating penalty costs. Howson(37) studied the relationship between hardness and soap use, and his results indicate an approximate linear relationship between hardness and annual soap cost per person. The equation applicable for the Lower Colorado River region is:

$$C = K_1 + K_2H \; ;$$

where: C = Annual per capita cost of all cleaning products,

H = Total hardness of the water supply in mg/l,

K_1 = \$8.224 when $H \geq 300$ mg/l and \$9.60 when $H < 300$ mg/l, and

K_2 = \$0.0128/mg/l when $H \geq 300$ mg/l and \$0.0084/mg/l when $H < 300$ mg/l.

In this case, K_1 represents the annual per capita expenditure for cleaning agents, whereas K_2H represents the annual per capita cost of cleaning agents lost through chemical association with water hardness. As hardness increases, this non-beneficial soap loss also increases. The detriments then are calculated as follows:

TOTAL DET = (C) (population affected);

where: TOTAL DET = Total detriments considered when undesirable effects of a degraded supply are accepted, and

C = Annual per capita cost associated with specific hardness.

The penalty cost is the difference between the two target years' "total detriments."

Penalty Cost = (C) (population affected)

Other forms of economic loss incident to a hard domestic water have been recognized, of which the following four seem most important:

(1) Accelerated depreciation and higher maintenance costs of hot-water appliances, pipe, and fittings due to scaling and corrosion;

(2) Higher fuel costs caused by heat losses in water heaters (these losses are a consequence of hard scale formation on heating coils, tubes, and similar fittings);

(3) More rapid wear of fabrics (clothing, linens) washed in hard water, owing to longer time needed for washing;

(4) Cost of bottled water for drinking and culinary uses (an unpalatable mineralized water supply may induce consumers to buy relatively expensive bottled water).

The sum of losses (1) and (2) has been reported from several different sources to range from \$22 to \$70 annually for a family of four persons. Available estimates of savings by use of soft water to offset excess fabric wear range from \$8 to \$75 annually per family. Although these losses are known to exist, several studies - including one conducted by a member of the Project staff in 1964 - have failed to find acceptable relationships between quality and incurred cost for these four effects. The Project staff concluded that it would be incorrect to assume any direct linear relationship between quality and user cost. Therefore, no attempt was made to evaluate losses associated with these four factors although it is recognized that such losses may outweigh those associated with soap and detergent wastage.

For this alternative it was assumed that part of the community would elect to purchase home softeners and the remainder would elect to incur increased costs for soaps and detergents to offset the increased hardness. The penalty costs associated with the use of home softeners is derived by:

$$\text{Penalty Costs (Home Softeners)} = P_1 b_1 - P_2 b_2 \; ;$$

where: P_1 = Number of people using home softeners with Colorado River water at the projected quality level,

b_1 = The unit cost of home softening at the corresponding water quality level, and

P_2, b_2 = similarly defined, except Colorado River water is taken at the 1960 quality level.

Estimates for total future population were provided the Project's economic contractor.(38) Field interviews with officials of individual water softening companies were made in order to determine the percentage of the present population using home softeners. The percentages of softener users for future water quality conditions were estimated from the information contained in Howson's article.(37) From these sources of information, a conservative range of increases (5 to 15 percent) in the percentage of people using softeners was assumed for future quality conditions.

The variables, b_1 and b_2, in the equation for home softener penalty costs represent the unit costs of home softening in dollars per capita per year. The values used for the "b" terms were derived empirically from rate schedules obtained in interviews with representatives of individual water softening companies. Although not all people employing home softening units do so on a rental basis, the unit cost of rented units compares favorably with the unit cost of purchased units if the purchase price is amortized over a ten-year period. For this reason the unit cost on a rental basis, which is easier to work with both conceptually and mathematically, was utilized in the determination of home softener detriments. An average family of three to five persons(39) and an average daily usage of softened water of 50 gallons per capita were used to determine the grain capacity of the softening unit required and "b" values referred to earlier.

Penalty costs for this alternative are also incurred by the portion of the community not using home softeners as reflected in increased cost of soaps and detergents. It should be noted that this is a consequence affecting only those persons who do not seek a remedy in water softening. The penalty costs for the second effect of this alternative are calculated by the following equation:

Penalty Costs (Non-Use of Home Softeners) $= C_1P_1 - C_2P_2$;

C_1 = Annual per capita costs associated with future hardness levels,

C_2 = Annual per capita costs associated with 1960 level of hardness, and

P_1, P_2 = Number of people not using home softeners at projected quality level and 1960 quality level, respectively.

The total penalty costs for this alternative are the sum of the penalty costs for the two effects.

Central Softening. Municipal users could elect to install central softening facilities as the third alternative. The detriments for this alternative are calculated as follows:

Detriments (Central Softening) $= Q \times \Delta H_1 \times d + (K_1 + K_2H_1)$;

Q = Annual volume of water treated,

ΔH_1 = The difference in hardness between the plant influent and effluent,

d = Unit operating cost of central softening expressed in dollars per 1,000 gallons per 100 mg/1 hardness removed,

K_1, K_2 = Constants defined under first alternative, and

H_1 = Hardness of the plant effluent.

Since a plant is usually designed for a particular quality effluent, the quality of the effluent remains constant. Thus, $H_2 = H_1$ so that the term $(K_1 + K_2H_1)$ cancels out. Penalty costs are therefore calculated as follows:

$$\text{Penalty Costs (Central Softening)} = Qd(\Delta H_2 - \Delta H_1) ;$$

ΔH_2 = Difference in hardness between a future target year quality and the plant effluent quality,

ΔH_1 = Difference in hardness between the 1960 quality and the same plant effluent quality.

If Q is in thousands of gallons per year, Δhardness is in mg/l, and d is expressed in terms of dollars per thousand gallons per 100 mg/l, the equation will yield penalty costs in dollars per year.

In the foregoing relationship, the appropriate values of Q were derived from various estimates in current literature of such organizations as the Bureau of Reclamation and the Arizona Water Company, and the values of Δhardness were derived from the Project's flow and salt routing model. The value of d was computed from data obtained in interviews with the officials of the specific central softening plant under consideration. The values compared closely with those developed by Howson who estimated the unit cost of central softening to be $0.05 per 1,000 gallons for the first 100 mg/l removed and $0.0125 per 1,000 gallons for each subsequent 100 mg/l removed. In all cases considered by the Project the differences in hardness were well above the 0-100 mg/l range; therefore, a d value of $0.0125 per 1,000 gallons per 100 mg/l hardness removed was used.

If central softening facilities are not available, the cost of building such a plant can be determined. The fixed costs for proposed plants were evaluated using a load factor of two-thirds, an assumed life of 50 years, and interest rates varying between 3-1/2 and 4-1/2 percent. The foregoing values correspond to current design practice and municipal bond interest rates in 1965, respectively. Although operating costs in existing softening plants vary considerably, an average value of $0.0125 per 1,000 gallons per 100 mg/l hardness removed was used in this study.

For this alternative, plants were evaluated for several levels of water supply hardness for which operating costs were calculated. These costs defined several points on a continuous cost-concentration function. The increase in costs over the range of increased hardness concentrations studied was taken as the penalty costs associated with this alternative.

Comparison of Alternatives. The penalty costs associated with each of the alternatives described were calculated for each major municipality in the geographic region studied. A comparison of these penalty costs for the Lower Main Stem study area is presented in Figure 11. Except for the Colorado River Aqueduct service area, the alternative resulting in highest penalty cost was home softening followed by central softening and soap wastage, in that order. This ranking undoubtedly reflects the fact that the soap-wastage method does not account for all the costs incurred. Nevertheless, the soap-wastage method was selected as the measure of municipal water use penalty costs for all municipal entities

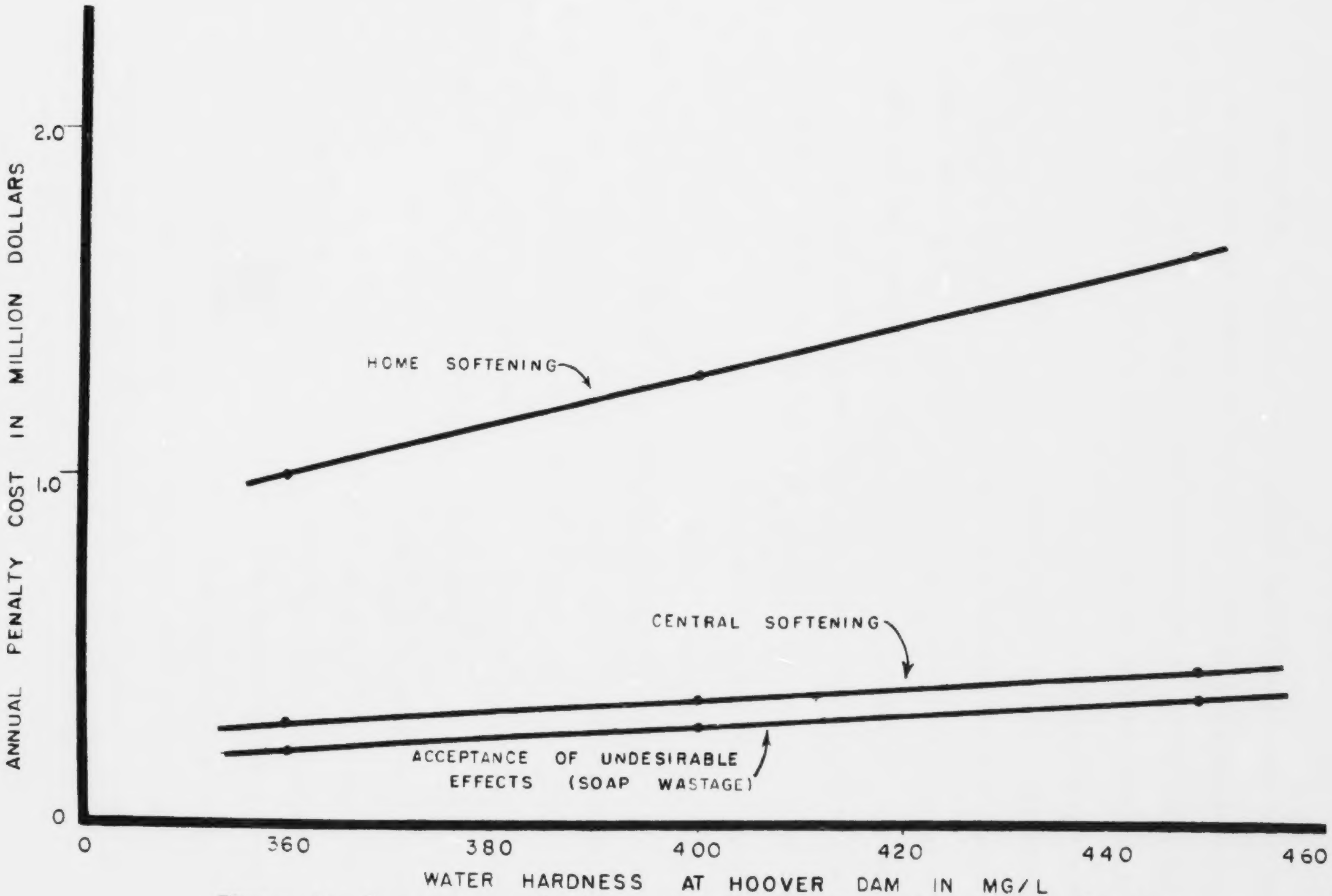


Figure 11. Comparison of Alternative Municipal Penalty Cost Evaluations in the Lower Main Stem Study Area – 1960

except those that actually have central softening plants. These are the Metropolitan Water District of Southern California and the city of Calexico, California, in the Southern California water service area. For these municipalities the central softening method was used to calculate penalty costs.

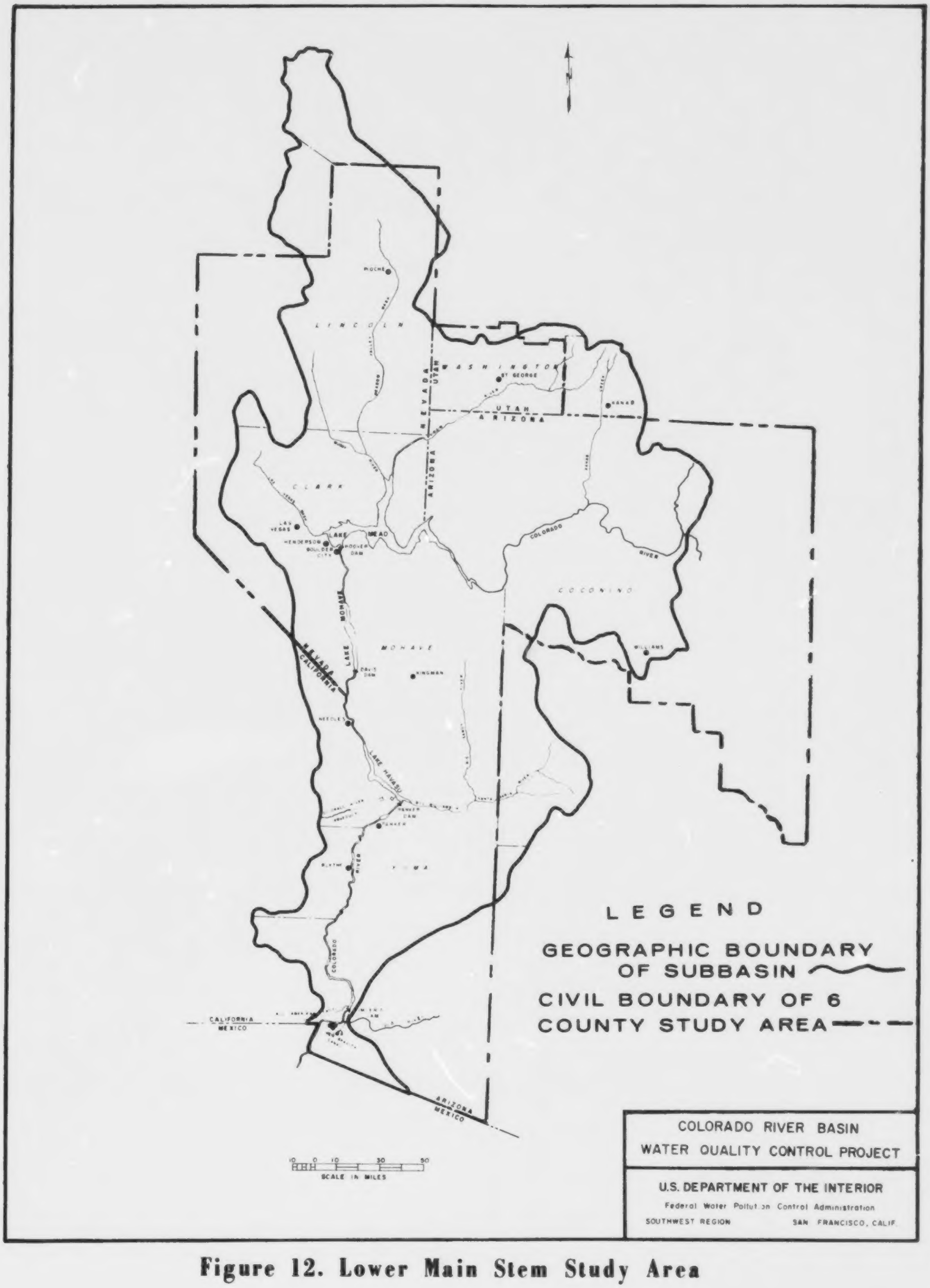
DETERMINATION OF DIRECT PENALTY COSTS

Direct economic impacts of projected changes in mineral quality of the Colorado River were determined for the three primary study areas (Figure 3): (1) Lower Main Stem, (2) Southern California, and (3) Gila. The determination of penalty costs associated with each area is discussed below. A summary of penalty costs for the entire area affected by quality changes begins on page 126.

Lower Main Stem Study Area (Figure 12)

Irrigated Agriculture Users Affected. The irrigation water users assessed penalty costs in the Lower Main Stem study area are all located in Yuma County, Arizona. Yuma County was divided into two areas: (1) Colorado River Indian Reservation, and (2) the remainder of Yuma County. A third area in the Lower Main Stem - including Washington County, Utah; Clark and Lincoln Counties, Nevada; and Coconino and Mohave Counties, Arizona - was studied, but the results of penalty cost assessments proved negligible. Table 16 summarizes data inputs which were assumed for penalty cost assessment for irrigation water uses.

Industrial Users Affected. Industrial water users are defined as all non-agricultural users other than municipalities. They include mining, manufacturing, trades and services, and all utilities. The percent of total use for boiler feed and cooling purposes was projected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LINCOLN
PIOCHE
WASHINGTON
ST GEORGE
KANAB
NEVADA
UTAH
ARIZONA
CLARK
LAS VEGAS
HENDERSON
BOULDER CITY
LAKE MEAD
HOOVER DAM
COLORADO
RIVER
COCONINO
WILLIAMS
LAKE MOHAVE
MOHAVE
DAVIS DAM
KINGMAN
NEVADA
CALIFORNIA
NEEDLES
LAKE HAVASU
PARKER DAM
PARKER
BLYTHE
RIVER
YUMA
COLORADO
CALIFORNIA
MEXICO
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10 0 10 30 50
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LEGEND
GEOGRAPHIC BOUNDARY OF SUBBASIN
CIVIL BOUNDARY OF 6 COUNTY STUDY AREA
COLORADO RIVER BASIN
WATER QUALITY CONTROL PROJECT
U.S. DEPARTMENT OF THE INTERIOR
Federal Water Pollution Control Administration
SOUTHWEST REGION
SAN FRANCISCO, CALIF.

Figure 12. Lower Main Stem Study Area

Table 16. Basic Data for Penalty Cost Assessment for Irrigated Agriculture in Lower Main Stem Study Area

Area	Major Crops Grown	Target Year	Acreage	Applied Amount (Acre-Feet)
Colorado River Indian Reservation	Barley, Sorghum Grain, Cotton	1960	30,461	126,500
		1980	84,525	406,600
		2010	101,360	483,000
Remainder of Yuma County		1960	153,085	760,700
Yuma Project	Cotton, Pasture, Alfalfa, Flaxseed, Grapefruit, Oranges, Tangerines, Lemons, Limes	1980	150,568	714,000
		2010	133,500	618,000
Gila Project	Alfalfa Hay, Cotton, Irrigated Pasture, Sorghums, Lemons, Limes, Oranges, Tangerines, Cantaloupes, Lettuce			

to remain at the 1960 level for all sectors except electrical energy which is the major heavy water use in the Lower Main Stem study area. Although recent trends indicate that this percentage is decreasing,(40, 41) it was felt that the majority of industrial users would not convert to more costly high tolerant systems. These users would, therefore, be forced to maintain the present relative percentage of boiler feed and cooling water usage. For the electrical energy sector, it was assumed that present volume of cooling and boiler feed water use by sensitive systems would remain constant over time although total use was projected to increase. This assumption resulted in projected percentages of 90, 11, and 3 for 1960, 1980, and 2010, respectively, for sensitive-system use relative to total intake requirement.

The intakes for industrial users of Colorado River water are located throughout the length of the study area. However, more than 75 percent of all industrial water consumed in the Lower Main Stem study area is diverted from Lake Mead to the Henderson, Nevada, industrial complex. Thus, it was assumed that all industrial diversions occurred at Lake Mead The target year mineral qualities at Lake Mead were, therefore, used as intake qualities for all industries in the Lower Main Stem study area. The relative magnitude of penalty costs did not warrant further refinement.

Municipal Users Affected. Five municipalities in the Lower Main Stem area will be affected by changes in the quality of Colorado River water. The target year populations served by Colorado River water (not necessarily the total populations) and the target year water qualities (hardness) at the respective points of diversion from the river are shown in Table 17.

Table 17. Municipalities Served by Colorado River Water in the Lower Main Stem Study Area

Municipality	Population Served[a]			Hardness ($CaCO_3$)[c] (mg/l)		
	1960	1980[b]	2010[b]	1960	1980	2010
Las Vegas, Nevada	42,500	141,000	272,000	345	420	460
Henderson, Nevada	17,000	39,000	75,000	345	420	460
Boulder City, Nevada	4,300	12,700	24,000	345	420	460
Parker, Arizona	1,500	4,000	7,000	340	415	460
Yuma, Arizona	30,000	58,000	101,000	370	485	540

---

a/ Population served by Colorado River water, not necessarily the total population.

b/ Population projections are Leasure's median projections.(38)

c/ Intake quality as developed in Project's salt and flow routing model.

Results of Analyses. Each individual user's water quality is directly related to the water quality at Hoover Dam, as shown in Table 17. As indicated in Chapter III, penalty costs incurred by each user were plotted versus Hoover Dam water qualities. Hoover Dam serves as a convenient reference point and is the major control structure on the river system below which all significant penalty costs are incurred. In fact all user intakes in the three study areas are located at or below Hoover Dam. The results of the direct penalty cost analyses are summarized in Table 18.

Table 18. Summary of Direct Penalty Costs in the Lower Main Stem Study Area

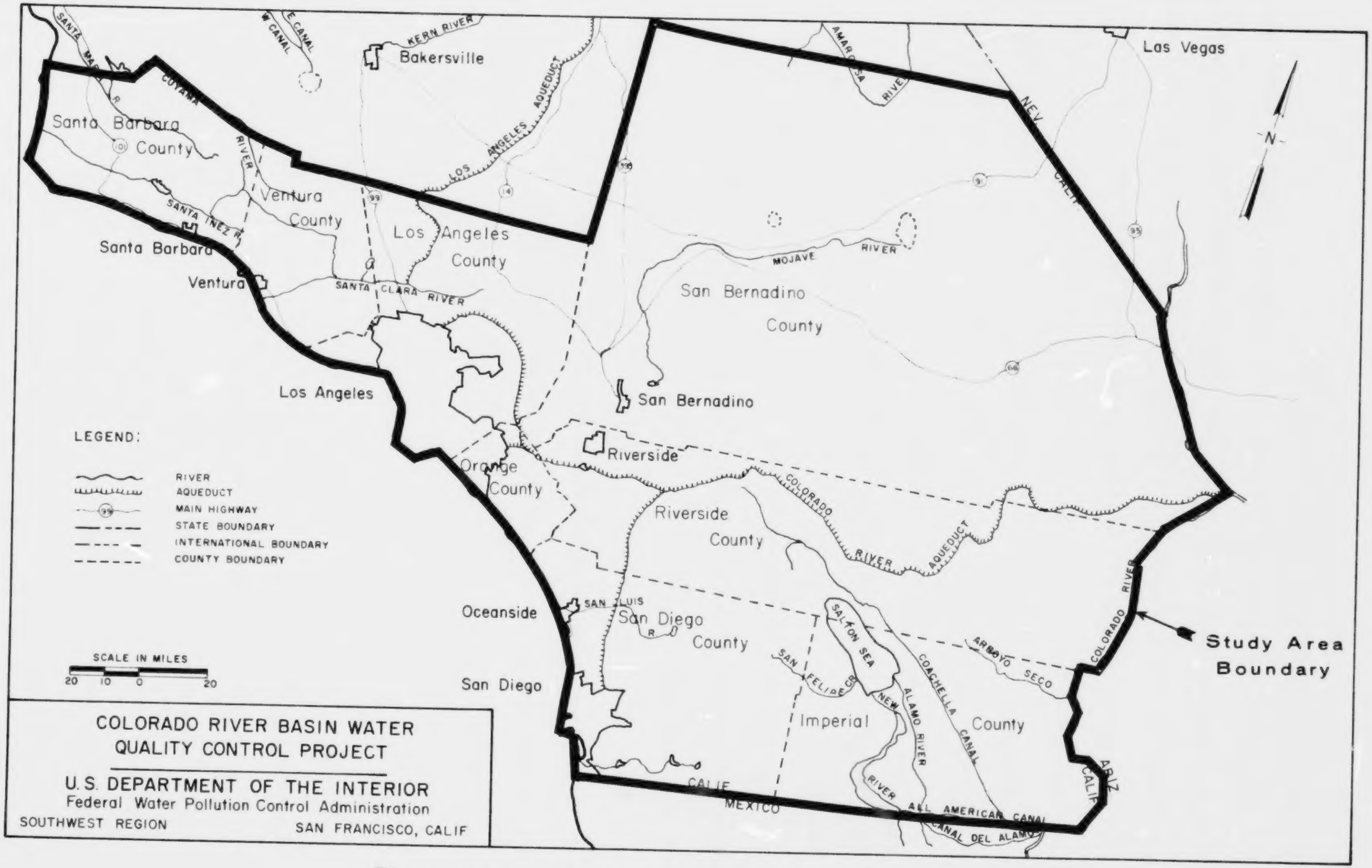
Type User	Target Years	
	1980	2010
	($1000 annually)	
Irrigated Agriculture	1,096.5	2,423.8
Municipal	275.0	779.0
Industrial	106.7	410.2
TOTAL	1,478.2	3,613.0

Southern California Study Area (Figure 13)

For convenience, all California lands receiving Colorado River water were included in this study area. The area is divided into three parts: one served by the Colorado River Aqueduct with diversion point at Parker Dam, one served by the All American Canal which originates at Imperial Dam, and the other comprising California lands along the Colorado River with varying diversion points. The total study area is shown in Figure 13, and the water distribution systems are shown more clearly in Figure 14.

Colorado River Aqueduct Service Area. A substantial blending of northern California water with Colorado River Aqueduct (CRA) water is expected by 1980. An increasing supply of northern California water of high quality will be delivered via the Foothill Feeder to MWD's present treatment plants at La Verne and Yorbe Linda, and probably also to a third plant near Pasadena proposed for construction in the 1980's.

An analysis of the possible effect on MWD water blended with northern California water was made assuming that the CAP delivery schedule is met. The results are summarized graphically in Figure 15. The upper curve shows that, based upon projected Colorado River quality degradation, the quality of MWD supply will continue degrading until 1971 when deliveries of northern California water are scheduled to begin and, thereafter, will improve rapidly to 550 mg/l by 1979, the date postulated for the beginning operation of the CAP. Assuming that the full load of the CAP is realized immediately, salinity levels in the blended MWD supply should drop to about 380 mg/l in the following year. Thereafter, over the next 35 years, there will be a long decline as gradually increasing amounts of high quality northern California water are brought


Las Vegas
N
NEV
CALIF
AMARGOSA RIVER
KERN RIVER
Bakersville
E CANAL
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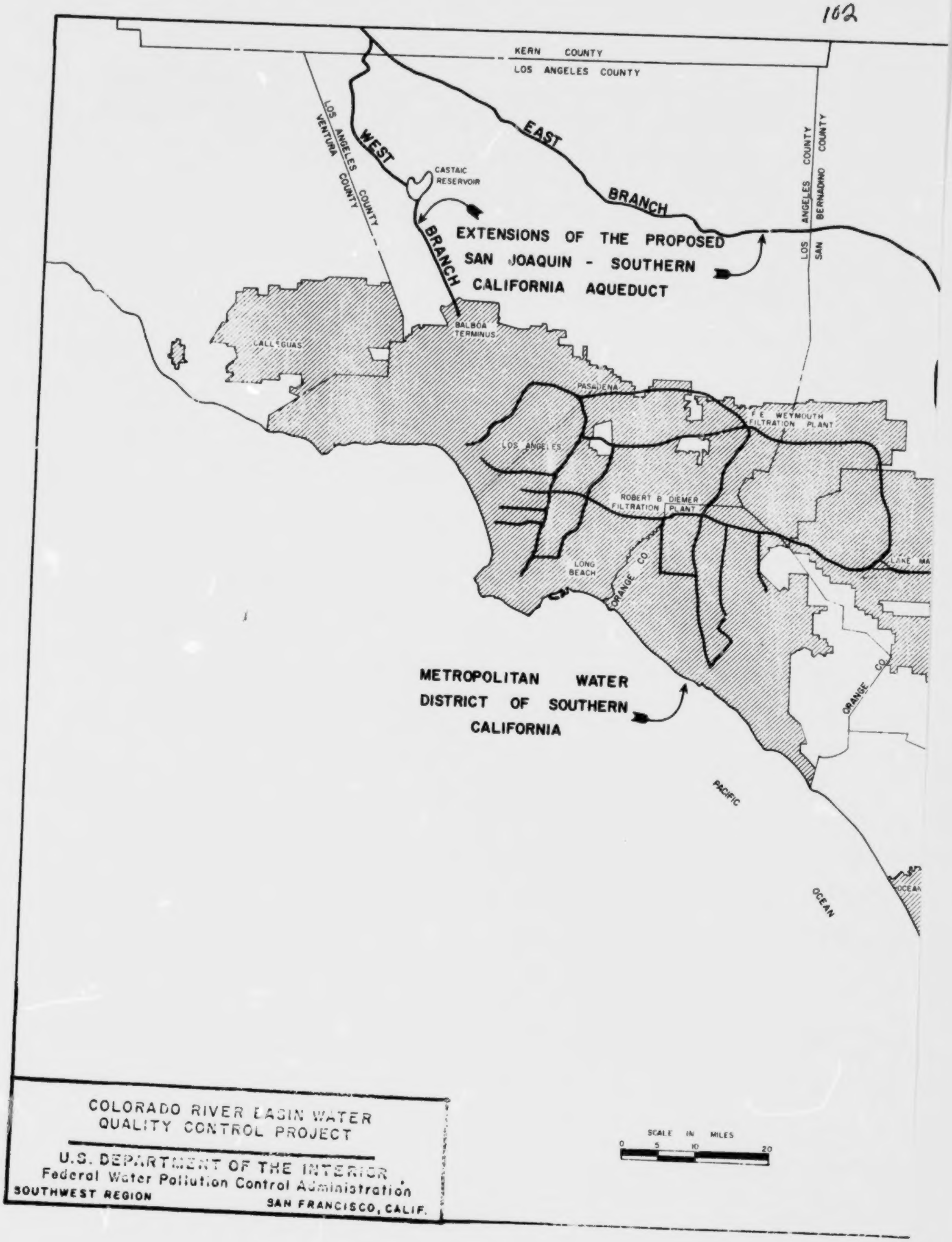
LOS ANGELES AQUEDUCT
CUYAMA RIVER
SANTA MARIA R
Santa Barbara County
Ventura County
Los Angeles County
SANTA INEZ R
Santa Barbara
Ventura
SANTA CLARA RIVER
Los Angeles
MOJAVE RIVER
San Bernadino County
San Bernadino
Riverside
Orange County
Riverside County
COLORADO RIVER AQUEDUCT
Oceanside
SAN LUIS R
San Diego County
San Diego
SALTON SEA
SAN FELIPE CR
NEW RIVER
ALAMO RIVER
COACHELLA CANAL
ARROYO SECO
Imperial County
COLORADO RIVER
ARIZ
CALIF
MEXICO
ALL AMERICAN CANAL
CANAL DEL ALAMO
Study Area Boundary
LEGEND:
RIVER
AQUEDUCT
MAIN HIGHWAY
STATE BOUNDARY
INTERNATIONAL BOUNDARY
COUNTY BOUNDARY
SCALE IN MILES
20 10 0 20
COLORADO RIVER BASIN WATER
QUALITY CONTROL PROJECT
U.S. DEPARTMENT OF THE INTERIOR
Federal Water Pollution Control Administration
SOUTHWEST REGION
SAN FRANCISCO, CALIF

Figure 13. Southern California Study Area


KERN COUNTY
LOS ANGELES COUNTY
LOS ANGELES COUNTY
VENTURA COUNTY
LOS ANGELES COUNTY
SAN BERNADINO COUNTY
WEST BRANCH
EAST BRANCH
CASTAIC RESERVOIR
EXTENSIONS OF THE PROPOSED SAN JOAQUIN - SOUTHERN CALIFORNIA AQUEDUCT
BALBOA TERMINUS
CALLEGUAS
PASADENA
LOS ANGELES
F.E. WEYMOUTH FILTRATION PLANT
ROBERT B. DIEMER FILTRATION PLANT
LONG BEACH
ORANGE CO.
LAKE MA
METROPOLITAN WATER DISTRICT OF SOUTHERN CALIFORNIA
PACIFIC
OCEAN
SCALE IN MILES
0
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10
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COLORADO RIVER BASIN WATER
QUALITY CONTROL PROJECT

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Federal Water Pollution Control Administration
SOUTHWEST REGION
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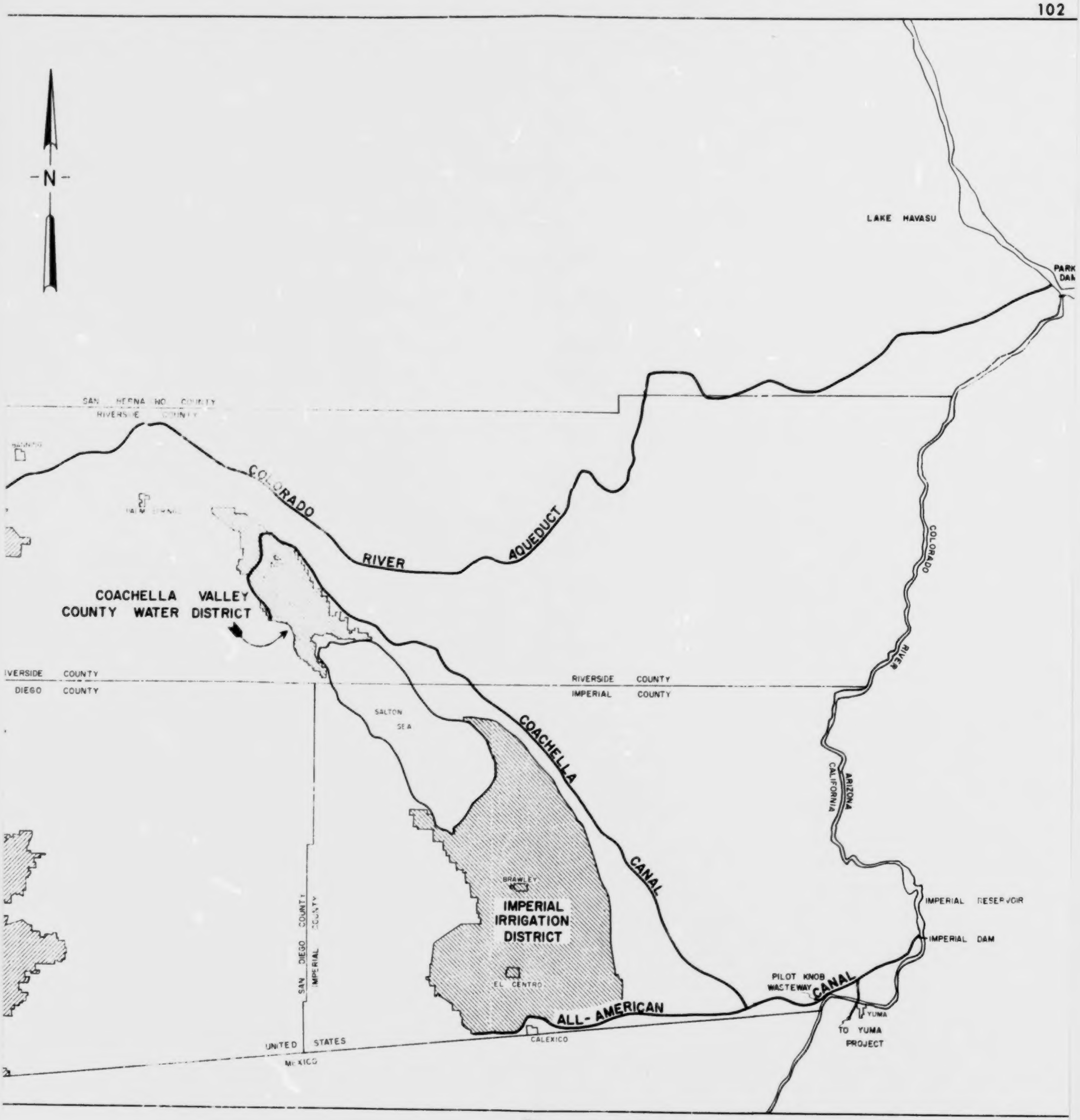
N
LAKE HAVASU
PARK DAM
SAN BERNARDINO COUNTY
RIVERSIDE COUNTY
PALM SPRINGS
COLORADO RIVER AQUEDUCT
COACHELLA VALLEY COUNTY WATER DISTRICT
RIVERSIDE COUNTY
DIEGO COUNTY
RIVERSIDE COUNTY
IMPERIAL COUNTY
SALTON SEA
COACHELLA CANAL
COLORADO RIVER
ARIZONA
CALIFORNIA
BRAWLEY
IMPERIAL IRRIGATION DISTRICT
EL CENTRO
SAN DIEGO COUNTY
IMPERIAL COUNTY
IMPERIAL RESERVOIR
IMPERIAL DAM
PILOT KNOB WASTEWAY
ALL-AMERICAN CANAL
YUMA
TO YUMA PROJECT
CALEXICO
UNITED STATES
MEXICO

Figure 14. Southern California Water Service Area

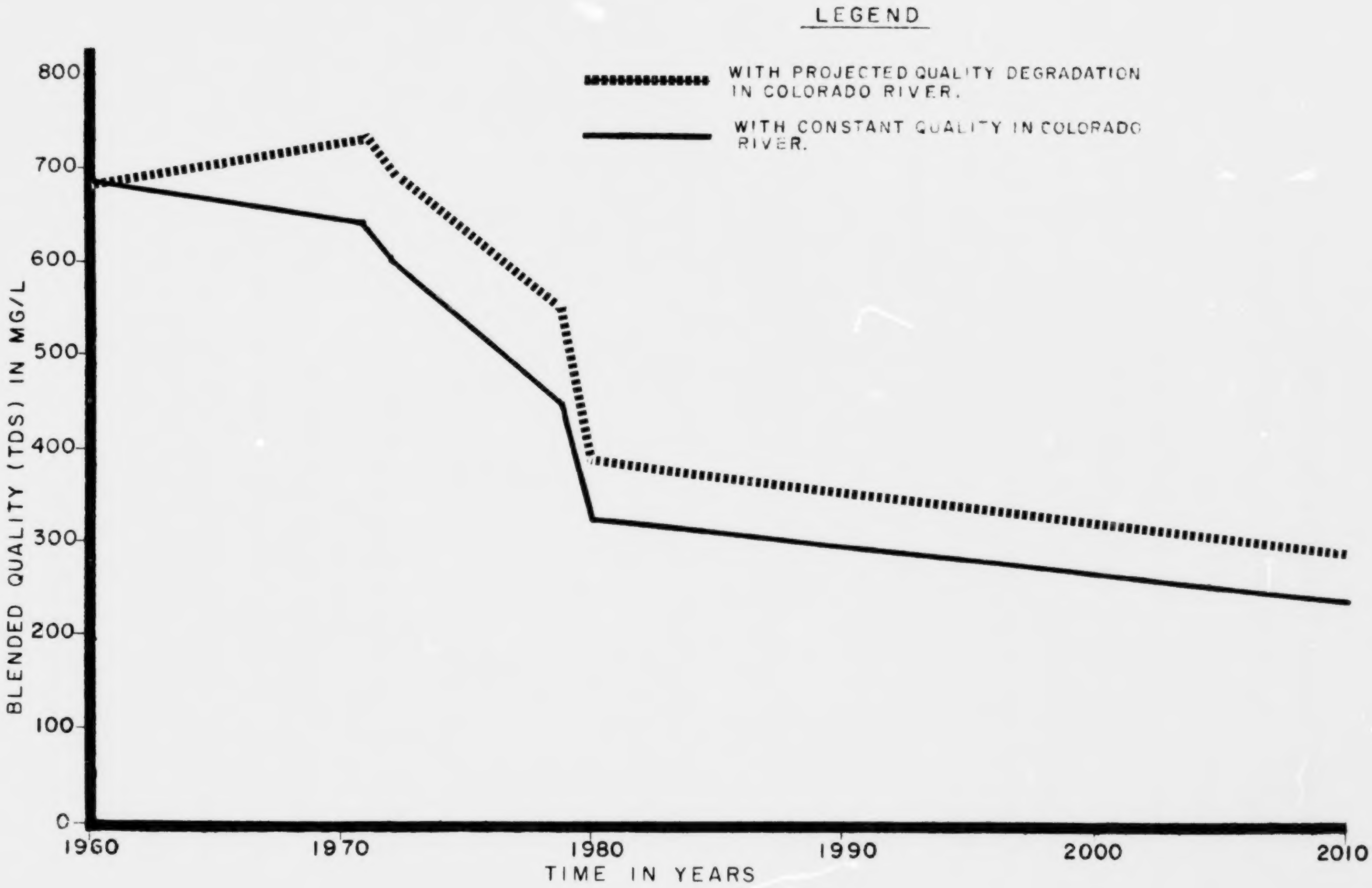

Figure 15. Quality of the Metropolitan Water District Blended Supply Composed of Colorado River and Feather River Water

in. In the year 2010 the quality of the blended MWD supply will be about 290 mg/l if quality degradation of Colorado River water continues at the projected rate.

The lower curve shows the consequences of an unchanging quality level in the Colorado River portion of the supply with total dissolved solids maintained constant at the 1960 value of 684 mg/l at Parker Dam. Therefore, use of Colorado River water affects the blended MWD supplies by 55 mg/l (325 to 380) in 1980 and by 50 mg/l (240 to 290) in 2010. A synoptic tabulation of anticipated changes in salinity of the MWD blended supply is shown in Table 19.

Table 19. Present and Projected Mineral Quality of Metropolitan Water District Blended Water Deliveries

Year	Colorado River Supply		Feather River Supply		Blended Supply	
	Volume (1000 AF/Yr)	TDS (mg/l)	Volume (1000 AF/Yr)	TDS (mg/l)	Quality (mg/l)	TDS[a] (mg/l)
1960	817	684			684	684
1971	1,105	784	95	160	740	640
1972	1,120	793	200	160	700	600
1979	1,212	857	956	160	550	450
1980	550	866	1,064	160	380	325
2010	550	985	2,635	160	290	240

---

[a] Blended quality assuming constant Colorado River salinity of 684 mg/l.

Agricultural Users Affected. The MWD provides an agricultural water supply to several constituent members. At the present time, the most prominent agricultural use member - the San Diego County Water Authority - distributes water to four irrigation districts in the western part of the county, and this pattern is expected to continue. The relationship between the total agricultural use of

MWD water and the agricultural use of MWD water supplied to the San Diego County Water Authority is shown in Table 20.

Table 20. Present and Projected Use of Metropolitan Water District Water for Irrigated Agriculture

Year	Total MWD Use[a] (Acre-Feet)	San Diego County Use[a] (Acre-Feet)
1960	119,160	39,700
1965	152,756	69,069
1980	161,000	110,000
2010	130,000	130,000

---

[a] Information obtained from personal contact with MWD personnel.

Three assumptions were made in order to evaluate the effects of changes in the quality of Colorado River water on the MWD users. The first assumption was that the cropping pattern of western San Diego County is representative of the cropping pattern in the total area served by the MWD. This assumption seems reasonable since the portion of MWD agricultural water used in San Diego County will increase until the year 2010 when all MWD agricultural water will be used in that area. The second assumption was that by the year 1980 the MWD deliveries would be a blend of 485,000 AF of Colorado River (684 mg/l) and 1.5 million AF of Feather River water (160 mg/l).[1] The third assumption was that the blended irrigation water would be diluted uniformly by an average annual effective local rainfall of nine inches[1] and that this water would be consumed by crops and other vegetation. (It should be recognized that the economic effects are dampened considerably by the last two assumptions.)

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[1] The blend of northern California and Colorado River water is based upon published delivery schedules assuming that CAP will be completed by 1980. MWD personnel have informed the Project that present plans are to divert 65,000 AF from the CRA directly to agricultural users in the San Diego area before any blending with northern California water. Therefore, the amount of Colorado River water which will be blended has been reduced from 550,000 AF to 485,000 AF.

Based upon the assumptions stated above, data were developed for use in calculating the direct economic penalty costs to the irrigation water users served by the MWD. These data are summarized in Table 21.

Table 21. Present and Projected Data Used in Evaluating the Direct Penalty Costs to Irrigation Water Users Served by the Metropolitan Water District

Target Year	Acreage (AC)	Amount Irrigation Water Applied (AF)	Effective Rainfall (AF)	Total Water Applied (AF)	Blended Quality (TDS) (mg/1)
1960	62,900	120,000	50,000	170,000	--
1980	83,100	160,000	66,000	226,000	409
2010	66,700	130,000	53,000	183,000	452

Industrial Users Affected. The Colorado River Aqueduct delivers water to the Metropolitan Water District of Southern California which, in turn, serves water users in a six-county area stretching from Ventura County to San Diego County (Figure 14).

Present total water use for the Southern California study areas was determined from available published data. Data for the MWD, which is the only entity served by the Colorado River Aqueduct, was obtained from State of California publications.(34) A summary of these data for the six-county area served by MWD is given in Table 22. Bulletin 78, California Department of Water Resources,(19) contains information indicating that 87 percent of the six-county area is served by MWD; however, only 28 percent of the water delivered by MWD is supplied by the Colorado River.[1] Therefore, the present total amount of industrial water supplied to Southern California via the CRA was estimated to be: (0.87)(0.28)(290,000) = 71,000 AF.

---

[1] "Effective rainfall" is defined as rainfall that is not lost by runoff during a storm and is not lost by evaporation from the ground surface after a storm. During the seasons 1932-1957, 15 inches of seasonal rainfall was exceeded only five times at Pomona, an area with higher rainfall than the study area. There were only three years in 25 that were likely to produce any leaching of lands under winter crops.(19)

Future intake requirements for the CRA were extrapolated from estimates of the probable ultimate industrial development and the ultimate delivery requirements per irrigated acre. An alternate calculation relating industrial use to projected urban demand produced a second approximation of intake requirements. From these two estimates, a total intake requirement of 825,000 AF was established for the year 2010 and 500,000 AF for the year 1980. Based upon the assumptions: (1) published delivery schedules for northern California water will be met; (2) Colorado River water will be delivered in accordance with the authorized schedule for the Central Arizona Project; (3) two-thirds of all water use is for cooling and boiler feed purposes;(5) and (4) industry will use local and imported waters in proportion to their general availability in the area, it was estimated that 215,000 AF of Colorado River water would be used for cooling and boiler feed

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[1] Records of MWD for water year 1962-63.

Table 22. Water Use by Manufacturing Industry in the Six Counties of the Metropolitan Water District of Southern California, 1957-1959

(Acre-Feet per year x 1000)

	Petrol. Ref	Food	Chem. & Allied	Paper	Stone, Clay & Glass	Fab. Metals	Transp. Eqpt.	Prim. Metals	Wood (Exc. Furn.)	Sub-Totals	% of County Totals	County Totals
SIC No.	29	20	28	26	32	34	37	33	24			
Los Angeles	75.3	32.4	22.0	19.6	7.2	20.6	16.3	5.6	0.5	199.5	89	224.2
Orange	2.6	4.8	2.0	1.1	0.1	0.8	0.9	0.5	0.4	13.2	74	17.9
San Diego	9.2	3.7	1.1	0.0	0.2	0.3	2.5	0.1	0.1	17.2	93	18.5
San Bernardino	0.2	2.0	0.3	0.0	5.6	0.1	0.1	6.5	1.4	16.2	93	17.5
Riverside	1.8	1.2	0.0	0.1	2.9	0.1	0.5	0.4	0.0	7.0	96	7.3
Ventura	0.4	1.7	0.7	0.6	0.2	0.0	0.0	0.0	0.4	4.0	92	4.4
											Grand Total	289.8
											or Approximately	290

purposes within the MWD in 1980 and 418,000 AF would be used for these purposes in 2010.

Incremental water requirements were calculated by the mathematical relationship discussed in the section entitled, "Methods of Penalty Cost Evaluation." The mineral quality of water delivered to industrial uses was assumed to deteriorate from 360 to 400 mg/l in 1980 and from 240 to 300 mg/l in 2010. Based on an average tolerance of 2,200 mg/l for sensitive industrial systems in the Colorado River Basin, additional water required to offset quality deterioration was estimated to be 455 AF/yr in 1980 and 735 AF/yr in 2010.

A unit cost of $35 per acre-foot was used to calculate the penalty cost associated with makeup water requirements in the MWD. Incremental treatment costs were derived from an industrial water-use survey made in 1959 by the National Aluminate Corporation.(42) Unit costs for treating cooling water generally ranged between three and seven cents per 1,000 gallons for internal treatment in Southern California with a bias toward the higher figure. The latter figure was used except where a lower cost was known to prevail.

A summary of pertinent data used to evaluate industrial penalty costs in the Southern California area is presented in Table 23.

Table 23. Projected Industrial Water Requirements for the Metropolitan Water District

Type of Use	1960 (AF)	1980 (AF)	2010 (AF)
Cooling Requirement	46,000	187,000	362,000
Boiler Feed Requirement	6,000	28,000	56,000

Municipal Users Affected. The MWD has two large water treatment plants. The older F. E. Weymouth Filtration and Softening Plant located near La Verne has a capacity of 400 mgd. Softening is done by a cation-exchange process. The large-scale and integrated nature of the operation (the district itself produces much of the sodium chloride needed for regeneration of the cation exchange materials) permits softening at a very low cost of less than 1-1/2 cents per 1,000 gallons. A new water treatment facility, the Robert B. Diemer Plant located near the community of Yorbe Linda, was dedicated in 1964. It has a filtration capacity of 200 mgd, but does not have any water-softening facilities.

Of the 550,000 AF/year assumed to be diverted from Lake Havasu in 1980 and 2010, the MWD municipal users are assessed the costs of softening 400,000 AF/year in both target years. The remaining unsoftened volumes are assumed filtered at the Diemer Plant and then blended with northern California water. Of these remaining volumes, it was assumed that agriculture would use 95,000 AF/year and 65,000 AF/year in 1980 and 2010, respectively. Only the softening expense makes up the penalty costs; the cost of filtering is, of course, not included.

Penalty cost assessments were based on central softening treatment cost of $0.125/1,000 gal/100 mg/l hardness removed. The present and projected municipal use of MWD water is shown in Table 24.

All American Canal Service Area.

Agricultural Users Affected. The All American Canal conveys water diverted at Imperial Dam to Imperial County and the Coachella

Table 24. Present and Projected Municipal Use of Metropolitan Water District Water

Target Year	Volume (AF)
1960	442,000
1980	400,000
2010	400,000

Valley Irrigation District. The present and projected acreages, amounts of applied water, and major crops grown in these areas are shown in Table 25.

Industrial Users Affected. Present industrial water intake requirements for the All American Canal service area were derived from existing data. Future demand was assumed to grow in strict proportion to sales of manufactured products. Based upon this assumption and considering that the relative ratio of boiler feed and cooling water use to total intake would remain constant, estimates of 125 AF/year in 1980 and 380 AF/year in 2010 were derived. Table 26 shows present and future intake water requirements. In addition to the amounts shown in the table, approximately 433 AF of water were consumed in steam-electric power generation in 1964. The annual projected intake requirements for this purpose are 860 AF in 1980 and 1,740 AF in 2010.

Industries served by the All American Canal use Colorado River water exclusively so that there are no effects caused by dilution water from other sources. The water quality at Imperial Dam was used as the intake quality in all cases for industries in this area. The significant industrial supply qualities for diversion

Table 25. Basic Data for Penalty Cost Assessment to Irrigated Agriculture, All American Canal Users

Area	Major Crops Grown	Target Year	Acreage	Water Applied (Acre-Feet)
Imperial County	Alfalfa, Barley, Vegetables	1960	489,716	2,426,700
		1980	560,000	2,704,000
		2010	529,000	2,552,000
Coachella Valley County Water District	Carrots, Grapes, and Cotton	1960	44,671	284,000
		1980	54,800	351,750
		2010	54,500	351,000

Table 26. Summary of Water Data Used for Industrial Penalty Cost Assessment in Imperial County, California

Year	Cooling (A-F/yr)	Boiler Feed (A-F/yr)	Process (A-F/yr)	Other (A-F/yr)	Total (A-F/yr)	Intake Quality (mg/l)
1960[a]	1,927	192	1,706	526	4,351	759
1965	2,670	270	2,360	560	5,860	---
1980	5,290	530	4,680	1,100	11,600[b]	1,056
2010	10,800	1,070	9,520	2,250	23,600[b]	1,223

---

a/ Based on 1957-1959 period.
b/ Values rounded.

and delivery points are summarized in Table 26.

Municipal Users Affected. As mentioned before, several communities in Imperial County get their water supply from the Colorado River via the All American Canal distribution system. These communities, listed in order of their population, are El Centro, Brawley, Calexico, Holtville, Imperial, Calipatria, Westmorland, and Niland. The present and projected populations of these communities are shown in Table 27.

Table 27. Present and Projected Populations of Imperial County Communities

Towns	1960	1980	2010
El Centro	18,300	25,800	45,400
Brawley	13,000	14,300	16,800
Calexico	8,900	12,600	22,300
All Others	11,200	15,000	22,500
Total	51,400	67,700	107,000

Only Calexico practices softening in a central municipal plant. Privately owned or rented water softeners are widely used in other communities because of the hardness of the supply (approximately 385 mg/l). A survey conducted in December of 1964 among several commercial water softening services and sales outlets indicated that between 2,500 and 3,000 water softeners are in use in Imperial County. A reasonable estimate of the total population using softened water in the valley would be 19,000 (9,000 in Calexico and 10,000 in the remaining communities). This is about 37 percent of the urban population. All of this group would be affected by rising costs of water softening if the hardness of the supply should increase. The remaining 63 percent of the population would also be injured, not by rising expense of treatment but rather by the necessity for heavier consumption of soap, etc., as previously described.

Other California Users. There are other users of Colorado River water located in California that are not served either by the MWD system or the All American Canal. These users, located along the Colorado River, are the Palo Verde Irrigation District and the communities of Needles and Blythe.

Agricultural Users Affected. Irrigation water for the Palo Verde district is diverted from the Palo Verde Diversion Dam located upstream from Blythe, California. The present and projected acreage of principal crops grown and amounts of applied water in the district are shown in Table 28.

Table 28. Principal Crops Grown, Present and Projected Irrigation Acreages, and Amounts of Applied Water in the Palo Verde Irrigation District

Principal Crops Grown	Target Year	Irrigated Acreage	Applied Irrigation Water (Acre-Feet)
Alfalfa, Cotton, Barley	1960	78,735	376,600
	1980	111,800	541,400
	2010	121,000	595,400

Municipal Users Affected. The towns of Needles and Blythe are located in California along the Colorado River and both get their municipal water supply from the river. For purposes of penalty cost assessment, they are included in the Southern California water service area. The present and projected populations of these two towns are shown in Table 29.

Table 29. Present and Projected Populations of Needles and Blythe, California

Town	1960	1980	2010
Needles	6,080	10,600	14,000
Blythe	6,000	13,900	18,500

Results of Analyses. The results of the penalty cost analyses for the MWD service area, the All American Canal service area, the "other California" area, and the total Southern California study area are summarized in Table 30.

Gila Study Area (Figure 16)

The Gila study area is defined by counties. It includes Maricopa, Pima, Pinal, Santa Cruz, Cochise, Graham, Greenlee, Gila, Yavapai, and Catron Counties.

Agricultural Users Affected. In order to evaluate the effect of salinity in the Central Arizona Project area, it was necessary to make four assumptions: (1) All Colorado River water deliveries will be used for irrigated agriculture, the least sensitive of all users; (2) there will be uniform mixing of agricultural supplies from all sources (ground, surface, and CAP deliveries); (3) the quality of ground water in the CAP area is the median or 50 percentile average quality of all ground water presently used; and (4) the quality of surface and ground water presently used will not change in time, and only CAP water delivered from the Colorado River will change.

Each of the above assumptions was designed to produce conservative

Table 30. Summary of Direct Penalty Costs Incurred by All Southern California Users of Colorado River Water

	1980				2010			
Type Users	Colorado River Aqueduct	All-American Canal	Other Calif.	Southern Calif. Study Area Total	Colorado River Aqueduct	All-American Canal	Other Calif.	Southern Calif. Study Area Total
		($1,000 annually)				($1,000 annually)		
Irrigated Agriculture	484.9	3,704.3	427.8	4,617.0	751.9	8,371.7	948.5	10,072.3
Industrial	49.4	6.8	---	56.2	79.7	22.9	---	102.6
Municipal	1,220.0	100.0	27.0	1,347.0	1,950.0	233.0	56.0	2,239.0
TOTAL	1,754.3	3,811.1	454.8	6,020.2	2,781.6	8,627.6	1,004.5	12,413.9

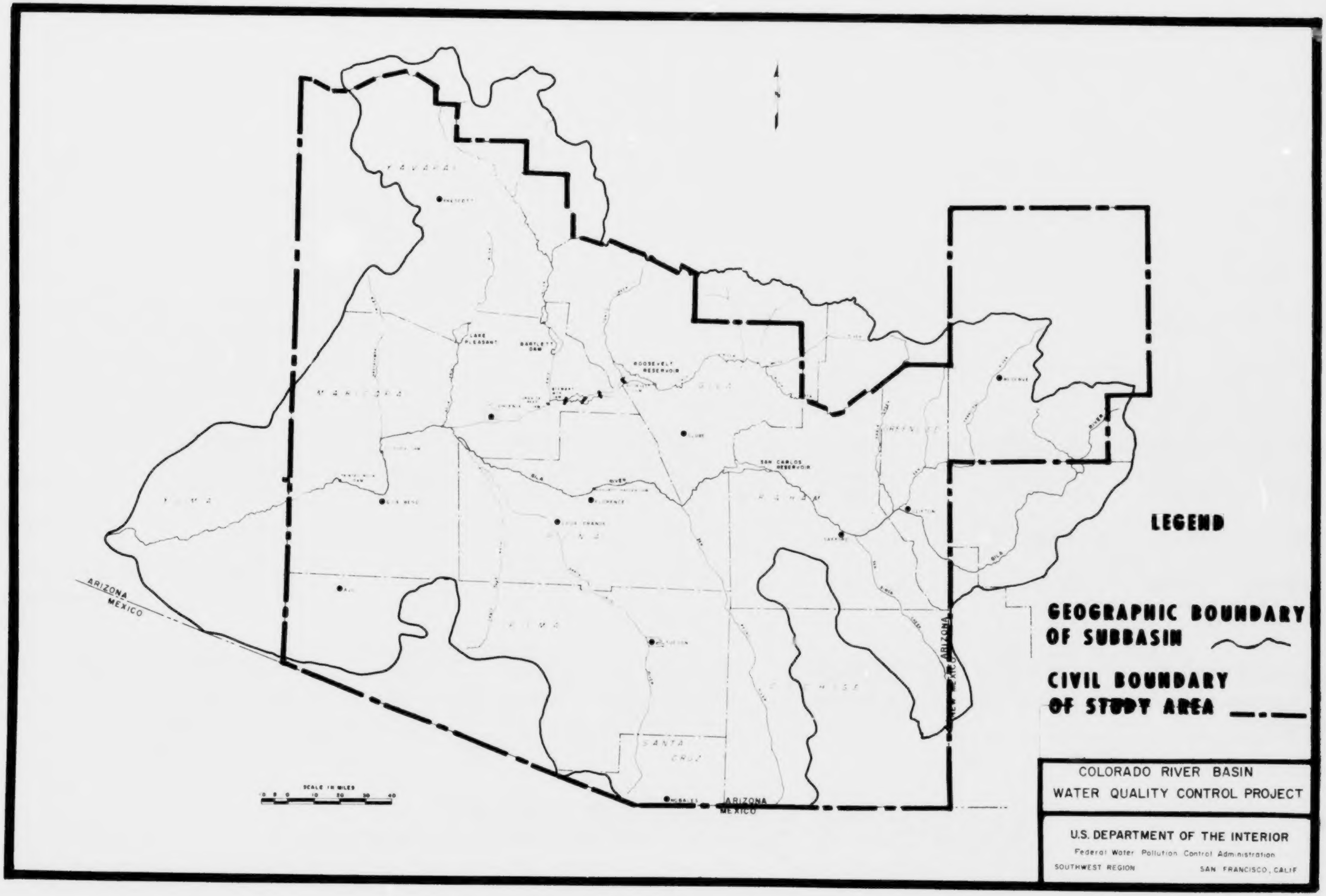
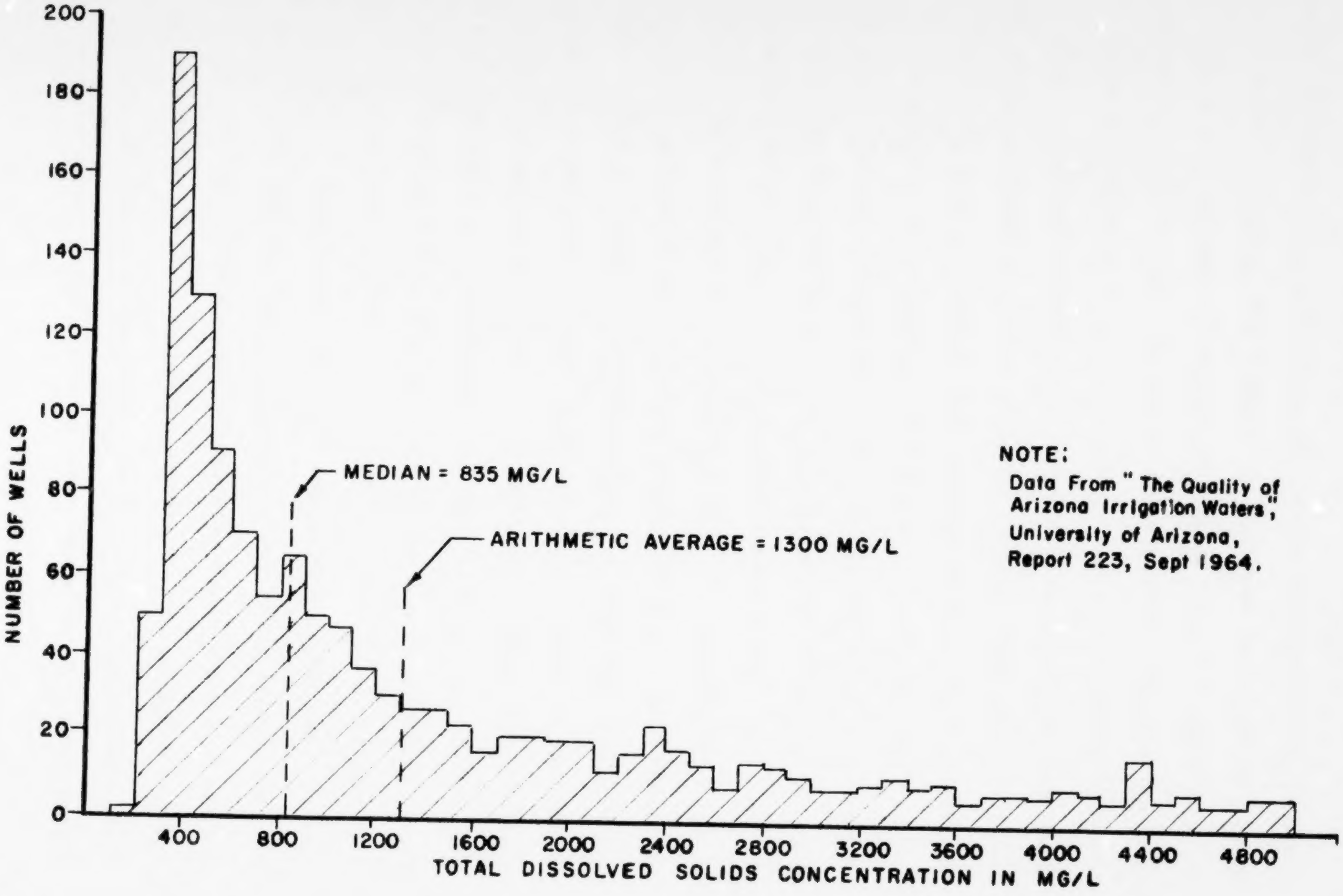

LEGEND
GEOGRAPHIC BOUNDARY OF SUBBASIN
CIVIL BOUNDARY OF STUDY AREA
COLORADO RIVER BASIN
WATER QUALITY CONTROL PROJECT
U.S. DEPARTMENT OF THE INTERIOR
Federal Water Pollution Control Administration
SOUTHWEST REGION
SAN FRANCISCO, CALIF
YAVAPAI
MARICOPA
YUMA
PIMA
PINAL
GILA
GRAHAM
GREENLEE
COCHISE
SANTA CRUZ
LAKE PLEASANT
BARTLETT DAM
ROOSEVELT RESERVOIR
SAN CARLOS RESERVOIR
GILA RIVER
FLORENCE
ARIZONA
MEXICO
NEW MEXICO
ARIZONA
ARIZONA
MEXICO
SCALE IN MILES
10 5 0 10 20 30 40

Figure 16. Gila Subbasin Study Area

estimates of total penalty costs. The assumptions were necessary because present and projected data were not adequate and, in some instances, not available. The first assumption implies that good quality ground water now used for irrigation will be exchanged for CAP water allocated to municipal use. Refining the second assumption would require operational data and projections of use (in many cases not available) from each individual water company, entailing a long and expensive survey and analysis. In the third assumption, quality of ground water used for irrigation was estimated at a median TDS concentration of 835 mg/l (Figure 17). A more representative flow-weighted average could have been computed if the volume of water and quality data were available for each well. The arithmetic average TDS concentrations for the wells is 1,300 mg/l (Figure 17). The fourth assumption was based on information obtained from knowledgeable persons in the Phoenix-Tucson area who indicated that separate analyses for each ground water basin would be required to identify quality trends. Preliminary attempts to identify quality trends using limited data were unsuccessful, primarily because ground water quality in the CAP area varies widely in composition and concentration both horizontally and vertically. This variance is not only related to the quality of the recharge waters, but also to the chemical changes occurring within the ground water mass.

The present (1960) and projected irrigated acreages were defined for the Gila study area by economic sector. From the aqueduct delivery and turnout points, it appeared that substantially all of Maricopa and Pinal Counties and portions of Pima County would receive CAP water or return flows. It was assumed that no area south of Tucson would be



MEDIAN = 835 MG/L

ARITHMETIC AVERAGE = 1300 MG/L

NOTE:
Data From " The Quality of Arizona Irrigation Waters", University of Arizona, Report 223, Sept 1964.

Figure 17. Mineral Quality of Ground Water Used for Irrigation in the Central Arizona Project Area

affected and that areas outside the Santa Cruz River Valley proper north of Tucson would not be affected. Thus, about 50 percent of the irrigated area of Pima County would be influenced. Therefore, all irrigated lands in Maricopa and Pinal Counties and half of those in Pima County were assessed agricultural salinity penalty costs.

A decline in irrigated acreage is projected for every county in the study area. Since the irrigated area affected by the CAP accounts for 81.5 percent of all acreage in the study area in 1960, it was assumed that the CAP area acreages would decrease in proportion to the total reduction in subbasin acreage. Water requirements for the CAP are shown in Table 31.

Table 31. Present and Projected Water Required for Agriculture in the Central Arizona Project Area

Year	Amount (1000 AF/Yr)
1960	3,482
1980	3,286
2010	2,923

The sources from which the water requirements will be met are shown in Table 32. The surface supply quality was estimated to be the average of the 1914-1958 hydrologic period as shown in Table 33.

Estimating an average ground water quality is subject to uncertainty due in part to a lack of both flow and quality data. Therefore, a statistical analysis of domestic and of irrigation ground water quality was made, based on data from two University of Arizona publications. (43, 44) The affected ground water areas were delineated as indicated

Table 32. Present and Projected Sources of Water for Irrigation in the CAP Area

Year	Sources			Total
	Surface	Ground	CAP	
		(1,000 A.F./Yr.)		
1960	723[a]	2,759	---	3,482
1980	723	1,606	957[b]	3,286
2010	723	1,627	573[b]	2,923

---

[a] Farm deliveries from diversion of 1,096,000 acre-feet.
[b] Applied CAP water assuming a 70 percent delivery efficiency to farm headgates.

Table 33. Quantity and Quality of Surface Waters Entering the CAP Area[a]

Source	Volume	TDS Quality (mg/l)
Agua Fria River at Lake Pleasant	100,600	210
Verde River at Bartlett Dam	454,800	240
Salt River at Stewart Dam	626,000	810
Gila River at Kelvin	356,000	600
Volume Weighted Average for all Supplies	---	555

---

[a] From Colorado River Basin Water Quality Control Project routing model.

in Figure 18. The distribution of mineral quality for wells in these areas is shown in Figure 17. The median TDS concentration is 835 mg/l while the flow-weighted mean is about 1,300 mg/l. The median and weighted mean for the domestic wells are 480 mg/l and 700 mg/l, respectively. It was assumed that the TDS concentration of ground water used for agriculture would be 835 mg/l in each target year.

Imported water is the third supply source. Mineral quality at Parker Dam, the diversion point, was projected by the routing model to be 866 mg/l in 1980 and 985 mg/l in 2010. Mineral quality at the point of delivery was estimated by computing the evaporation losses (concentrating effects) incurred in transit. These losses were determined by subtracting the seepage losses from the total losses. Bureau of Reclamation estimates of total losses on the order of 10 percent of total volume were used. The dimensions of the proposed aqueduct and the coefficient of permeability of the concrete lining were obtained from Bureau of Reclamation reports and were used in computing the seepage losses. Based on these calculations, the qualities at the point of delivery were estimated to be 920 mg/l and 1,010 mg/l in 1980 and 2010, respectively.

The penalty cost assessment was based on the schedule of deliveries presented in the 1967 Hearings on the Central Arizona Project before the U. S. Senate Subcommittee on Water and Power

Major crops grown, irrigated acreages, and the amount and quality of applied irrigation water in 1960 and projections for 1980 and 2010 are shown in Table 34.

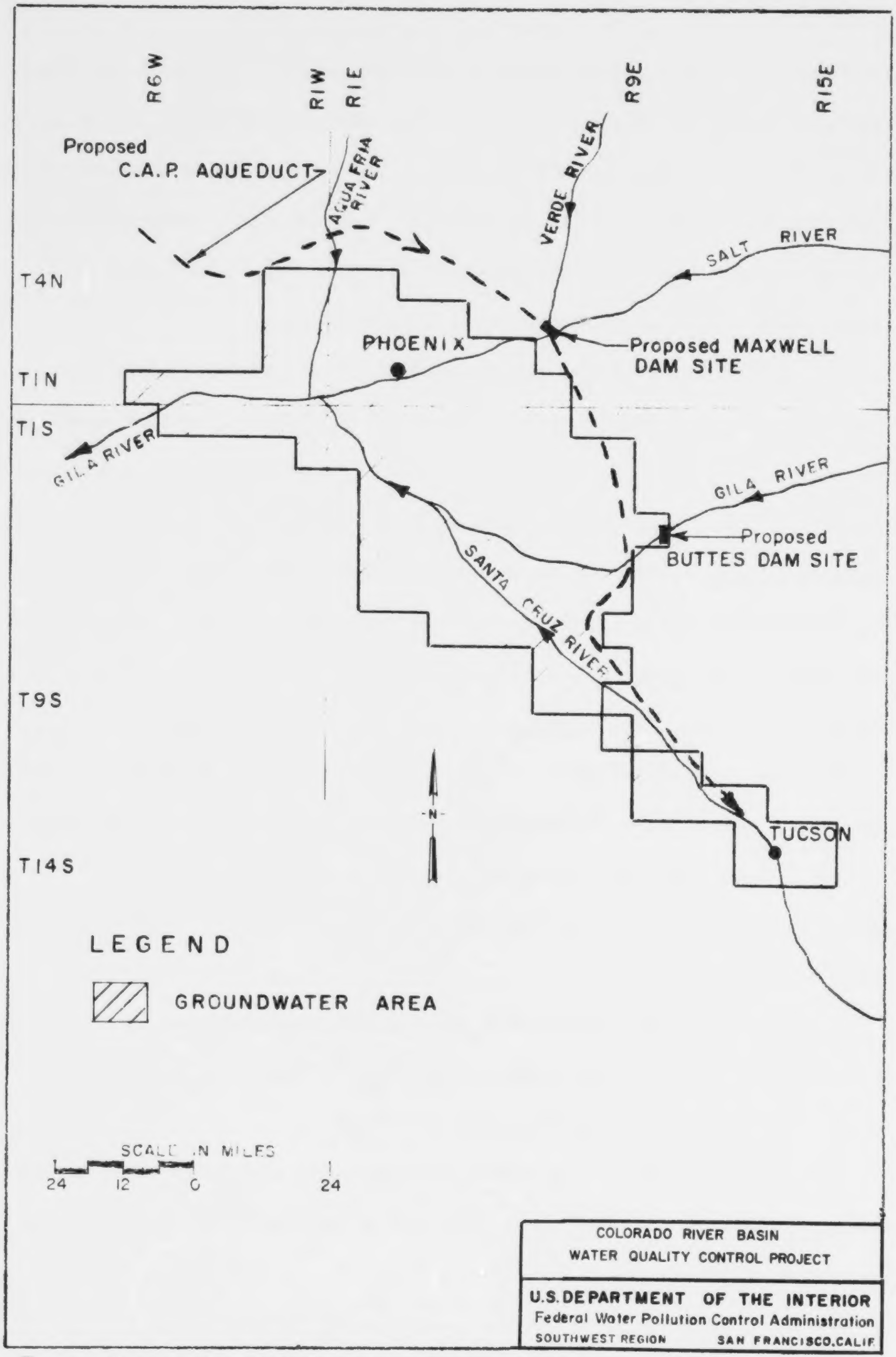

R6W
R1W
R1E
R9E
R15E
T4N
T1N
T1S
T9S
T14S
Proposed C.A.P. AQUEDUCT
AGUA FRIA RIVER
VERDE RIVER
SALT RIVER
PHOENIX
Proposed MAXWELL DAM SITE
GILA RIVER
GILA RIVER
Proposed BUTTES DAM SITE
SANTA CRUZ RIVER
TUCSON
N
LEGEND
▨ GROUNDWATER AREA
SCALE IN MILES
24
12
0
24
COLORADO RIVER BASIN
WATER QUALITY CONTROL PROJECT
U.S. DEPARTMENT OF THE INTERIOR
Federal Water Pollution Control Administration
SOUTHWEST REGION
SAN FRANCISCO, CALIF.

Figure 18. Location of Major Groundwater Areas in the Central Arizona Project Area

Table 34. Major Crops Grown, Present and Projected Irrigated Acreages, and Amounts and Quality of Applied Irrigation Water in the Central Arizona Project Area

Major Crops Grown	Year	Acreage	Applied Amount (AF)	Blended Quality (TDS) (mg/l)
Cotton, alfalfa, barley	1960	835,700	3,482,000	777
	1980	771,000	3,286,000	796
	2010	630,000	2,923,000	800

Existing surface and ground water supplies made up the 1960 requirement since there was no Colorado River water used in that year. The effect of the CAP is shown from 1980 to 2010. There is no salinity penalty cost in 1980 - the assumed water delivery date for the CAP.

Industrial and Municipal Users Affected. According to the assumptions previously discussed, all CAP water would be used for irrigated agriculture. Based on this assumption, there would be no industrial and municipal users affected by quality degradation of Colorado River water.

Results of Analyses. There would be no penalty costs in 1980, the assumed base year for this analysis. The use of 1980 as a base for the CAP analysis is comparable to the use of 1960 as a base for analyses of other areas.

Again, the purpose of this study was to measure external diseconomies caused by the degradation of Colorado River water only. In the CAP area it was anticipated that the Colorado River would provide no more than 30 percent of all agricultural water. Thus, the effects of the water quality degradations of the blended supply are diminished at least three-fold, based on the assumption that the qualities of all other supplies would remain constant over time as previously discussed. The results of the direct penalty cost analyses are shown in Table 35.

Summary of Lower Basin and Southern California Areas

The results of the analyses of direct penalty costs are summarized in Table 36 and Figure 19. Based upon this analysis, the total direct penalty cost in 1980 due to mineral quality degradation of Colorado River water would be $7.5 million. The projected total for year 2010 would be $16.3 million. It should be noted that more than 75 percent of the total direct penalties in both target years will be incurred by irrigated agricultural users.

Table 35. Summary of Direct Penalty Cost in the Gila Study Area

Type	1980 (In $1,000 Annually)	2010 (In $1,000 Annually)
Agricultural	0	245.7
Industrial	0	---[a]
Municipal	0	---[a]
TOTAL	0	245.7

---

[a] All CAP water is assumed to be used for irrigated agriculture.

Table 36. Summary of Direct Penalty Costs in the Lower Colorado Basin

Type	1980 (In $1,000 Annually)	2010 (In $1,000 Annually)
Irrigated Agriculture	5,713.5	12,741.8
Industry	162.9	512.8
Municipalities	1,622.0	3,018.0
TOTAL	7,498.4	16,272.6

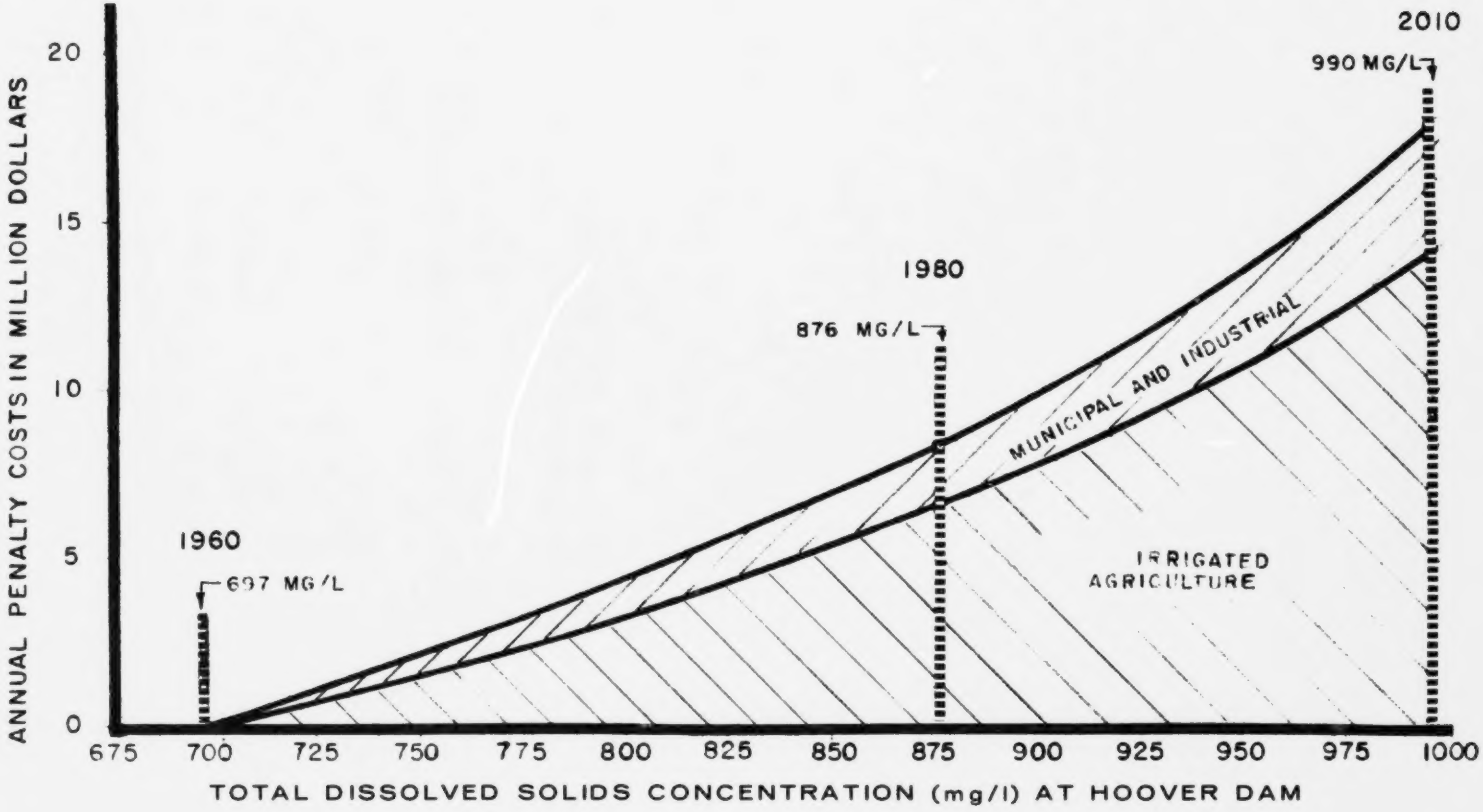


Figure 19. Summary of Direct Penalty Costs Incurred in the Lower Colorado River Basin & Southern California Study Areas

CHAPTER V. REGION-WIDE ECONOMIC IMPACT

INTERDEPENDENCE OF ECONOMIC ACTIVITIES

In addition to the direct economic effects of salinity upon beneficial users of water, there are numerous indirect effects which are brought about by the interdependence of economic activities. These effects are observed in nearly every sphere of economic activity and can be calculated when the dependency of each economic sector upon other sectors is known. Examples of the interdependence between economic activities are discussed in this section.

Water quality degradation of an industrial source causes either a direct loss of production or added costs of treatment and water purchases in order to maintain production. The former situation leads to decreased demands for other resource inputs to the production process forcing the supplier of such input resources to reduce his production. This secondary, or indirect effect, continues in a domino-like sequence until all such interdependent relationships have been exhausted. Added costs of production, the latter situation, induces indirect costs through a misallocation of resources (expenditures for treatment versus expenditures for productive purposes) representing a loss to the optimum regional economic output.

Similar effects are observed in other sectors of the economy. A decrease in the output of agriculture products leads to both direct and indirect decreases in the output of all other industries due to regional economic interdependence. Agriculture decreases its purchases from dependent industries and these industries in turn decrease their purchases from dependent industries until all reduced demands are satisfied. The economy settles back to a new demand-supply relationship.

The purpose of this chapter is to describe the methodology used to calculate the indirect economic effects of water quality degradation.

INPUT-OUTPUT MODEL

The technique and underlying assumptions of input-output analysis are well documented.(45) This chapter is concerned with the application of the model to evaluate mineral quality degradation effects. This type of analysis depends basically on a transaction table. This table is described succinctly by Miernyk[1/] as follows:

> "The transactions table simultaneously describes the demand-supply relationships of an economy in equilibrium. It describes the economy as it is, not as it should be, on the basis of some criterion or set of criteria. The table does not tell us whether the economy is operating at peak efficiency -- it does show the final demand for goods and services and the interindustry transactions required to satisfy that demand."

The input-output table is essentially a record of sales and purchases for each of the sectors defined in the table. The table describes the demand-and-supply relationship of the region's economy for the year designated.

[1/] Miernyk, William H., "The Element of Input-Output Analyses," New York Random House, 1965, Library of Congress No. 65-23339, p. 30. (Reference No. 45)

Construction of the input-output table for a given year is the first of several steps. From the I-O table, a matrix of requirements (direct coefficients) from each industry per dollar of adjusted gross output for each industry is computed, and a corresponding table of interdependence (Direct-Indirect) coefficients is derived. The interdependence coefficients take into account the direct and indirect effects on all industries of changes in final demand for any one industry.

To illustrate the use of this tool, a simplified version of a model composed of the agricultural, mining, and manufacturing sectors will be discussed. Symbolic transactions for this simplified version of the economy are shown in Figure 20. The portion of the transactions table enclosed in black lines is defined as the processing sector.[1/] Reading across the top row, A_1. A_2, A_3, and DA represent total sales (TA) by agriculture. Reading down the left column, A_1, M_1, F_1, and PA represent total purchases (TPA) by agriculture. The same procedures apply for mining and manufacturing. The expression in mathematical terms for the agriculture sector

$$TA = A_1 + A_2 + A_3 + DA, \text{ and} \tag{1}$$

$$TPA = A_1 + M_1 + F_1 + PA \tag{2}$$

applied equally with different symbols for the mining and manufacturing sectors. Thus, gross output (TA) minus intermediate use (A_1, A_2, and A_3) equals final use (DA) for the total system.

[1/] A sector may be defined as a single industry such as mining, or a group of industries such as referred to in the table. The meaning in each case should be clear from the context.

		Industry Purchasing				
		Agriculture	Mining	Manufacturing	Final Demand	Total Gross Output
Industry Selling	Agriculture	A_1	A_2	A_3	DA	TA
	Mining	M_1	M_2	M_3	DM	TM
	Manufacturing	F_1	F_2	F_3	DF	TF
Final Payments		PA	PM	PF	DP	(TP)
Total Gross Outlay		TPA	TPM	TPF	(TD)	

Figure 20. Illustrative Transactions Table

The equation form of the table is more useful for analytical purposes. As described earlier, the direct coefficients show the direct purchases by each sector from every other sector per dollar of output. Thus, for agriculture we can define a direct coefficient as follows:[1]

$$a_{11} = \frac{A_1}{TPA}, \qquad (3)$$

$$a_{21} = \frac{M_1}{TPA}, \text{ and} \qquad (4)$$

$$a_{31} = \frac{F_1}{TPA}. \qquad (5)$$

The production function (equation 2) may be replaced by its equivalent form:

$$TPA = a_{11}\ TPA + a_{21}\ TPA + a_{31}\ TPA + PA, \qquad (6)$$

or, since TPA = TA,

$$TA = a_{11}\ TA + a_{21}\ TA + a_{31}\ TA + PA.^{1/} \qquad (7)$$

Originally the sales distribution equations were defined as:

$$TA = A_1 + A_2 + A_3 + DA, \qquad (8)$$

$$TM = M_1 + M_2 + M_3 + DM, \text{ and} \qquad (9)$$

$$TF = F_1 + F_2 + F_3 + DF. \qquad (10)$$

If direct coefficients are defined for the mining and manufacturing sectors, these may be rewritten as follows:

$$TA = a_{11}\ TA + a_{12}\ TM + a_{13}\ TF + DA, \qquad (11)$$

$$TM = a_{21}\ TA + a_{22}\ TM + a_{23}\ TF + DM, \text{ and} \qquad (12)$$

$$TF = a_{31}\ TA + a_{32}\ TM + a_{33}\ TF + DF. \qquad (13)$$

---

[1] This simplified description overlooks problems of inventory adjustment, margining and so on which are important to the process but not to illustration of the logic. For a detailed discussion, see Reference No. 46.

These equations in standard form are written:

$$(a_{11} -1)\ TA + a_{12}\ TM + a_{13}\ TF + DA = 0, \tag{14}$$

$$a_{21}\ TA + (a_{22} -1)\ TM + a_{23}\ TF + DM = 0, \text{ and} \tag{15}$$

$$a_{31}\ TA + a_{32}\ TM + (a_{33} -1)\ TF + DF = 0. \tag{16}$$

The same equations in the notation of matrix algebra are written:

$$\begin{bmatrix} a_{11}-1 & a_{12} & a_{13} \\ a_{21} & a_{22}-1 & a_{23} \\ a_{31} & a_{32} & a_{33}-1 \end{bmatrix} \times \begin{bmatrix} TA \\ TM \\ TF \end{bmatrix} + \begin{bmatrix} DA \\ DM \\ DF \end{bmatrix} = 0. \tag{17}$$

In short hand notation the same equations are written:

$$\begin{bmatrix} A - I \end{bmatrix} \begin{bmatrix} T \end{bmatrix} + \begin{bmatrix} D \end{bmatrix} = 0, \tag{18}$$

or solving for the level of total output $\begin{bmatrix} T \end{bmatrix}$,

$$\begin{bmatrix} T \end{bmatrix} = \begin{bmatrix} I - A \end{bmatrix}^{-1} \times \begin{bmatrix} D \end{bmatrix}. \tag{19}$$

Equation (19) is the "model" used for evaluating the indirect effects of salinity upon the Colorado River Basin economy. This model may be used to evaluate constraints on output, T; changes in economic structure, A; or changes in demand patterns, D. Although the notation of equation (19) is used throughout this section, it is necessary to emphasize that the effect of changing any individual transaction in the initial table can be evaluated by the model. Thus, equation (19) is merely a short hand notation which indicates the mathematical form of the economic model.

EVALUATION OF TOTAL SALINITY EFFECTS

Because economic activities are interrelated, any change leads the economy to adjust to a new equilibrium condition. Economic changes directly related to water quality degradation were evaluated by using the economic model to determine their influence on the regional economic equilibrium. Total changes in the conditions of economic equilibrium attributable to water quality degradation are defined as the "direct and indirect" effects.

With the analytical model of the economy described in the preceding section, it is possible to evaluate three principal kinds of potential decisions or courses of action: (1) decisions which affect the availability of resources; (2) decisions which affect the demand for goods and services; (3) decisions which affect the production processes. Each of these decisions may deal with either absolute or relative changes, e.g., one can consider limits on the availability of a particular resource, or changes in patterns of resource use through substitution. Furthermore, the decisions are not mutually exclusive. Changes in the production process may implicitly involve changes in: (1) patterns of resource use; (2) demand; (3) resource employment; and (4) production.

The first step in analysis of the direct and indirect economic impact of water quality is to determine what alternative decisions are available to a water user who is confronted with water quality degradation. The direct economic effect of each alternative decision is then identified, and the results are quantified. These steps, taken together, constitute the process of "direct penalty cost assessment" described and evaluated in the preceding chapter. The penalty cost is then injected into the model in order to determine its effect on the regional economy. Different procedures are used to evaluate the effect of each type of potential water quality decision. These procedures are discussed in more detail in the following sections.

Agricultural Penalty Costs

Direct penalty costs incurred by agricultural sectors are interpreted as causing a resource constraint. The cost of developing additional water is the principal factor limiting present and projected future agricultural development. In response to an increment of water quality degradation, an irrigator can increase water use, reduce acreage, or incur a yield loss. As previously indicated, results from the yield decrement method of analysis were chosen as representative of the direct agricultural penalty costs. However, regardless of the penalty cost assessment method used, the effective water supply is diminished by reducing the yield per acre foot. Therefore, the effect of water quality degradation is to constrain agricultural development. In the case of irrigated agriculture it was assumed that any reduction in output would result in fewer consumer and export sales rather than fewer interindustry sales. Consider the definition of the aggregated input-output model presented previously:

$$T = \left[I - A\right]^{-1} D; \tag{20}$$

if $R = \left[I - A\right]^{-1}$, the equation takes the form

$$T = RD, \tag{21}$$

or

$$\begin{bmatrix} TA \\ TM \\ TF \end{bmatrix} = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix} \times \begin{bmatrix} DA \\ DM \\ DF \end{bmatrix}, \tag{22}$$

or expanding by the rules of vector algebra

$$TA = r_{11}\,DA + r_{12}\,DM + r_{13}\,DF, \tag{23}$$

$$TM = r_{21}\,DA + r_{22}\,DM + r_{23}\,DF, \text{ and} \tag{24}$$

$$TF = r_{31}\,DA + r_{32}\,DM + r_{33}\,DF. \tag{25}$$

In the above equations, r's are referred to as direct and indirect coefficients. These coefficients are fixed by the values of a, the direct coefficients. It is apparent from equations (24) and (25) that if D_1 were to change, because of a constraint on the level of T_1, then T_2 and T_3 would also change. In this simple illustrative case, the magnitude of the change may be easily determined.

From equation (23)

$$\Delta DA = \frac{\Delta TA}{r_{11}} ; \qquad (26)$$

where ΔTA is the direct penalty cost (determined by the yield decrement technique),

ΔDA is the associated reduction in consumer and export sales, and

r_{11} is the direct-indirect coefficient.

The direct and indirect economic impact of water quality costs is defined as the sum of TGO changes in all sectors, corresponding to the final demand change, Δ DA, in the first sector:

$$TEA_1 = \sum_{i=1}^{3} \Delta T_i = \Delta TA + \Delta TM = \Delta TF. \qquad (27)$$

Values of ΔTM and ΔTF can be determined from equations (24) and (25) as follows:

$$\Delta TM = r_{21} \Delta DA = r_{21} \frac{\Delta TA}{r_{11}}, \text{ and} \qquad (28)$$

$$\Delta TF = r_{31} \Delta DA = r_{31} \frac{\Delta TA}{r_{11}}. \qquad (29)$$

Substituting these values into equation (27) gives:

$$TEA_1 = \frac{\Delta TA}{r_{11}} \left(\sum_{i=1}^{3} r_{i1} \right) = \frac{\Delta TA}{r_{11}} (r_{11} + r_{21} + r_{31}), \qquad (30)$$

or $$TEA_1 = \Delta TA \; PM_1; \qquad (31)$$

where TEA_1 = Total economic effect of costs incurred by the agricultural sector, and

PM_1 = Water quality cost multiplier (Note: that the multiplier is always greater than 1.0, and that it is determined by the structure of the economy).

$$PM = 1 + \frac{r_{21}}{r_{11}} + \frac{r_{31}}{r_{11}} + \ldots; \text{ where } r_{ij} > 0; \text{ therefore,}$$

$$PM > 1, \text{ and } PM = f(a) \text{ since } R = \left[I - A \right]^{-1}.$$

Industrial Penalty Costs

Direct penalty costs incurred by industries in sectors other than agriculture cause changes in the economic structure. For example, in order to offset the effect of water quality degradation, the industrial water users provide a higher level of treatment for the existing supply or divert, treat, use, and discharge an additional quantity of water. The cost of obtaining or treating the additional water is the direct penalty cost. Such additional costs are identified sector-by-sector and entered in the model.

Water purchased from local governmental entities is assumed to be an expenditure otherwise distributed in the form of income or profit in the final payments sector. Since payments to local governmental entities are also composited in the final payments sector, a payment for additional water is exactly compensating. Since both sector entries are outside the processing sector (refer to Figure 20) there is no interdependence effect and the direct cost of the water purchase is taken as the total cost. This cost is determined by summing the water use cost for each sector:

$$WUC = \sum_{i=1}^{m} WUC_i ; \qquad (32)$$

where m is the number of affected sectors.

Treatment costs of the increment of water required to offset quality degradation is considered to be an increase in the retail sales of water treatment chemicals to the affected industry. To reflect this increase, the corresponding direct coefficient is changed and the model is used to produce a new transaction table. The procedure is illustrated for a simplified model as follows: Assuming a direct effect of "X" dollars, a new direct coefficient is defined.

$$A'_{22} = \frac{A_{22}\,Tm + X}{TM} \qquad (33)$$

$$= A_{22} + \frac{X}{TM}. \qquad (34)$$

This coefficient increases the transaction amount entered in the intersection of row 2 and column 2 of the model by an amount[1] "X".

The second step in calculating indirect costs is to substitute A' into equation (12), and to obtain a new set of solutions[2] for the set of equations (11), (12), and (13). The new set of solutions, as represented by TA', TM', and TF' are:

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[1] The actual amount of the increase is determined by multiplying the direct effect by a trade margin. For a discussion of trade margins, see Reference No. 46.

[2] The solution given by the model is: $T^* = [I - A^*]^{-1} D$; where A^* is identical to A except for element A_{22} which has been replaced by A'_{22}.

$$TA' = A_{11}\ TA' + A_{12}\ TM' + A_{13}\ TF' + DA, \tag{35}$$

$$TM' = A_{21}\ TA' + A_{22}\ TM' + A_{23}\ TF' + DM, \text{ and} \tag{36}$$

$$TF' = A_{31}\ TA' + A_{32}\ TM' + A_{33}\ TF' + DF. \tag{37}$$

The combined direct-and-indirect effect of water quality due to the increased demand for chemicals per unit of manufacturing sector output is defined as the total increase in gross economic output:

$$\begin{aligned} TEM_1 &= (TA' - TA) + (TM' - TM) + (TF' - TF) \\ &= \sum_{i=1}^{n} T'_i - T_i. \end{aligned} \tag{38}$$

In the general case, where more than one industrial sector may incur water user penalty costs, the detriments are defined as the total of the detriments incurred by each sector as follows:

$$TEM = \sum_{i=1}^{m} TEM_i; \tag{39}$$

m = the number of industrial sectors, and TEM_i is the value obtained from equation (38) for each sector.

Two important aspects of this procedure should be pointed out. The first is that direct and indirect penalty costs calculated according to equation (39) are determined for each sector of the model and summed. This procedure is based on the desire to associate the indirect effects of each element of assessed user cost with its source. The step-by-step process also identifies those industries which have a relatively large "secondary" effect (strong interdependence) associated with a moderate direct cost. This so-called "innocent industry" effect is discussed more fully in "An Interindustry Analysis of the Colorado River Basin in 1960 with Projections to 1980 and 2010," University of Colorado, Boulder, Colorado, June, 1968.(46)

The second important aspect is that an increase in gross output is interpreted as a penalty cost. This stems from the fact that more chemical inputs are required to produce at the same level (delivery of goods and services to final demand) in each sector directly affected by water quality. The model measures the increased inputs (costs) required from all other sectors even though the regional level of production remains unchanged. The effects of the increase in resource inputs required to sustain the same level of production is an indication of the regional economic cost of offsetting the impact of water quality.

Municipal Penalty Costs

The effects of increased hardness of water in domestic or municipal uses can be partially evaluated through the cost of softening or demineralizing. In areas where softeners are not used the effects can be measured by the additional outlays for soap and detergents, plumbing repairs, and the like. Thus, the direct municipal penalty costs for degradation of water quality are represented by two effects: increased treatment costs incurred by municipal and private softening plants, and the increased cost of soap and detergents used by individual households. The impact of these direct costs are observed mainly in the trades, services, and government sectors.

Increased treatment costs by municipalities (local government sector) are offset by additional charges or taxes to the consumers, thereby reducing household profits or income. However, since both households and local government are components of the final demand sector (outside the processing sector), the net effect is zero. On the other hand, the purchase of additional chemicals by local government from the trade sector (source of supply for chemicals) and the change in household purchasing patterns in order to purchase additional soap and detergents alter the resulting outputs of the model. The underlying assumption concerning households is that income previously allocated to what might be termed "luxury items" (eating out, incidental services, etc.) will be reallocated to the retail sector to purchase more soap and detergents. To properly handle such factors, a rather detailed procedure is required to adjust the model for the municipal and domestic penalty costs.

The first step in the procedure is to determine the percentage of household purchases allocated to each sector. This is accomplished by dividing the household final demand entry (purchase) in the affected sectors (trades and services) by the total of all household purchases as shown by the equation:

$$h_i = \frac{HH_i}{\sum_{i=1}^{n} HH_i} ; \qquad (40)$$

where h_i = the percentage of household expenditures allocated to the i^{th} sector,

HH_i = the dollar amount of household purchases from the i^{th} sector, and n = the number of all sectors in the economy including processing and final payments sectors.

The next step is to determine the relative reduction in final demand in each of the effected sectors, which are Eating and Drinking, Retail Trade, and Services. These changes are assumed to be proportional to the relative percentage of household expenditures:

$$r_q = \frac{h_q}{h_q+h_r+h_s}, \tag{41}$$

$$r_r = \frac{h_r}{h_q+h_r+h_s}, \text{ and} \tag{42}$$

$$r_s = \frac{h_s}{h_q+h_r+h_s}; \tag{43}$$

where r is the relative reduction in final demand, and Subscripts q, r, and s refer to the eating and drinking, retail trade, and services sectors, respectively.

The next step is to calculate a Final Demand Change Coefficient as follows:

$$d_q = r_q \sum_{i=1}^{m} h_i, \tag{44}$$

$$d_r = r_r \sum_{i=1}^{m} h_i, \text{ and} \tag{45}$$

$$d_s = r_s \sum_{i=1}^{m} h_s; \tag{46}$$

where d is the final demand change coefficient, and m is the number of processing sectors.

The actual change in final demand, corresponding to a direct municipal penalty cost of X is determined as follows:

$$\Delta D_q = -d_q T_q X, \tag{47}$$

$$\Delta D_r = -d_q T_q X + T_q X \tag{48}$$

$$= T_q \ (1 - d_q) \ X, \text{ and}$$

$$\Delta D_s = -d_s T_s X; \tag{49}$$

where ΔD is the change in final demand,

T is the trade margin for the sector indicated, and

d is the final demand change coefficient.

It should be noted that all three final demand changes are entered simultaneously in the model in order to determine total direct and indirect detriments. In this case, total costs are defined as:

$$TMD = \sum_{i=1}^{m} \left| TGO'_i - TGO_i \right| \ ; \tag{50}$$

where m = the number of sectors in the processing sector,

TGO_i is the output of the $i^{\underline{th}}$ sector before adjustment of final demands,

TGO'_i is the output of the $i^{\underline{th}}$ sector subsequent to adjustment of the final demands, and

the symbol $\left| \quad \right|$ means that the absolute value is to be considered; or that all differences are considered to be positive.

TOTAL EFFECT OF WATER QUALITY DEGRADATION

The total effect of water quality degradation is determined by summing the direct and indirect penalty costs for agricultural, industrial and municipal (household) sectors:

TEC = TEA + WVC + TEM + TEH;

where TEC is the total direct and indirect effect of quality deterioration on the subbasin,

TEA is the total direct and indirect economic impact of agricultural detriments,

(WVC + TEM) is the total direct and indirect economic impact of industrial penalty costs, and

TEH is the total direct and indirect economic impact of municipal penalty costs

Again, it is important to note that each of the above measures of cost has been determined by calculating the impact of a direct penalty cost on the economic equilibrium of the unconstrained (with regard to water quality) subbasin economy. The model was used to measure the total effect of water quality degradation. In some cases, as a result of the measurement technique, the shift is in the direction of increasing dollar value of economic output, at a constant level of production while other cases have led to direct decreases in the level of production, therefore, encompassing both income and production effects. If these effects were to be considered simultaneously, changes in dollar value of output would be partially self-cancelling. The result would be a projection of the actual condition of the economy under the influence of a water quality constraint. Such a projection is relevant to the development of a complete economic base study and is considered in the Economics Volume of the Project's Report. It should be noted, however, that one may not arrive at indirect costs by comparing the constrained economic projection with the unconstrained projection. Conversely, one cannot arrive at the constrained projection by comparing direct and indirect penalty costs with the unconstrained economic projection. For these reasons, a sector-by-sector breakdown of the direct and indirect costs has not been presented. Instead, direct and indirect costs are presented by study area total, with a breakdown for the major categories (irrigated agriculture, industrial and municipal) discussed previously (Tables 37, 38, and 39). The results are also shown graphically in Figure 21 for the Lower Main Stem study area, in Figure 22 for the Southern California study area, and in Figure 23 for the Gila study area. Total direct and indirect penalty costs for all three study areas are estimated to be $11.0 million in 1980 and $25.4 million in 2010.

SENSITIVITY OF MODEL TO FLOW INPUT DATA

Sensitivity analysis is a technique used to determine the contribution which each variable makes to the uncertainty of results obtained in a study such as this one. The specific purpose of this section is to determine sensitivity of penalty costs to variations in flow. Mineral quality of the Colorado River at a specific location and time is determined by the quantity of water and salt load carried in the river. As discussed in Chapter III, the analysis of mineral quality was based on the flow period 1942 to 1961, modified to 1960 conditions. However, since various other base periods could have been used, it was deemed advisable to analyze other flow conditions in order to determine whether the results and conclusions would change significantly under these conditions. As an extreme limit, the minimum compact delivery at Lees Ferry was chosen for the sensitivity analysis. This reduced water supply

Table 37. Input-Output Model Results for the Lower Main Stem Study Area

	1980	2010
	($1,000 annually)	
Agricultural Penalty Costs		
Direct	1,096.5	2,423.8
Indirect	765.4	2,237.2
Total	1,861.9	4,661.0
Industrial Penalty Costs		
Direct	106.7	410.2
Indirect	3.8	14.5
Total	110.5	424.7
Municipal Penalty Costs		
Direct	275.0	779.0
Indirect	13.6	39.3
Total	288.6	818.3
Total Direct Penalty Costs	1,478.2	3,613.0
Total Indirect Penalty Costs	782.8	2,291.0
Total Penalty Costs	2,261.0	5,904.0

Table 38. Input-Output Model Results for the Southern California Study Area

	1980	2010
	($1,000 annually)	
Agriculture Penalty Costs		
Direct	4,617.0	10,072.3
Indirect	2,447.0	6,194.5
Total	7,064.0	16,266.8
Industrial Penalty Costs		
Direct	56.2	102.6
Indirect	2.9	5.5
Total	59.1	108.1
Municipal Penalty Costs		
Direct	1,347.0	2,239.0
Indirect	304.8	506.6
Total	1,651.8	2,745.6
Total Direct Penalty Costs	6,020.2	12,413.9
Total Indirect Penalty Costs	2,754.7	6,706.6
Total Penalty Costs	8,774.9	19,120.5

Table 39. Input-Output Model Results for the Gila Study Area

	1980	2010
	($1,000 annually)	
Agricultural Penalty Costs[a]		
Direct	0	245.7
Indirect	0	125.4
Total	0	371.1

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[a] No penalty costs were assessed to municipal or industrial users. For explanation see Chapter II.

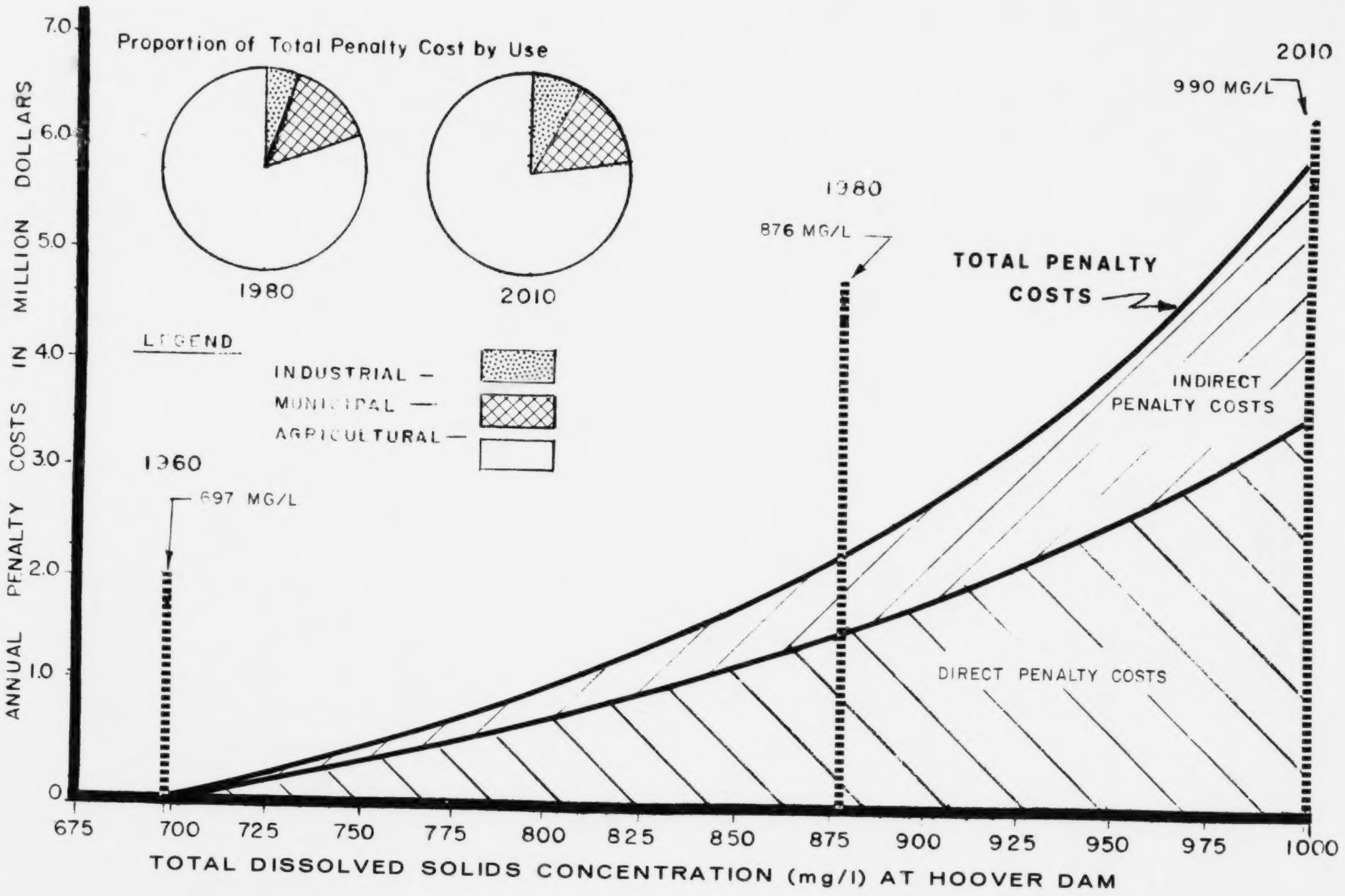

Figure 21. Total Penalty Costs Incurred in the Lower Main Stem Study Area

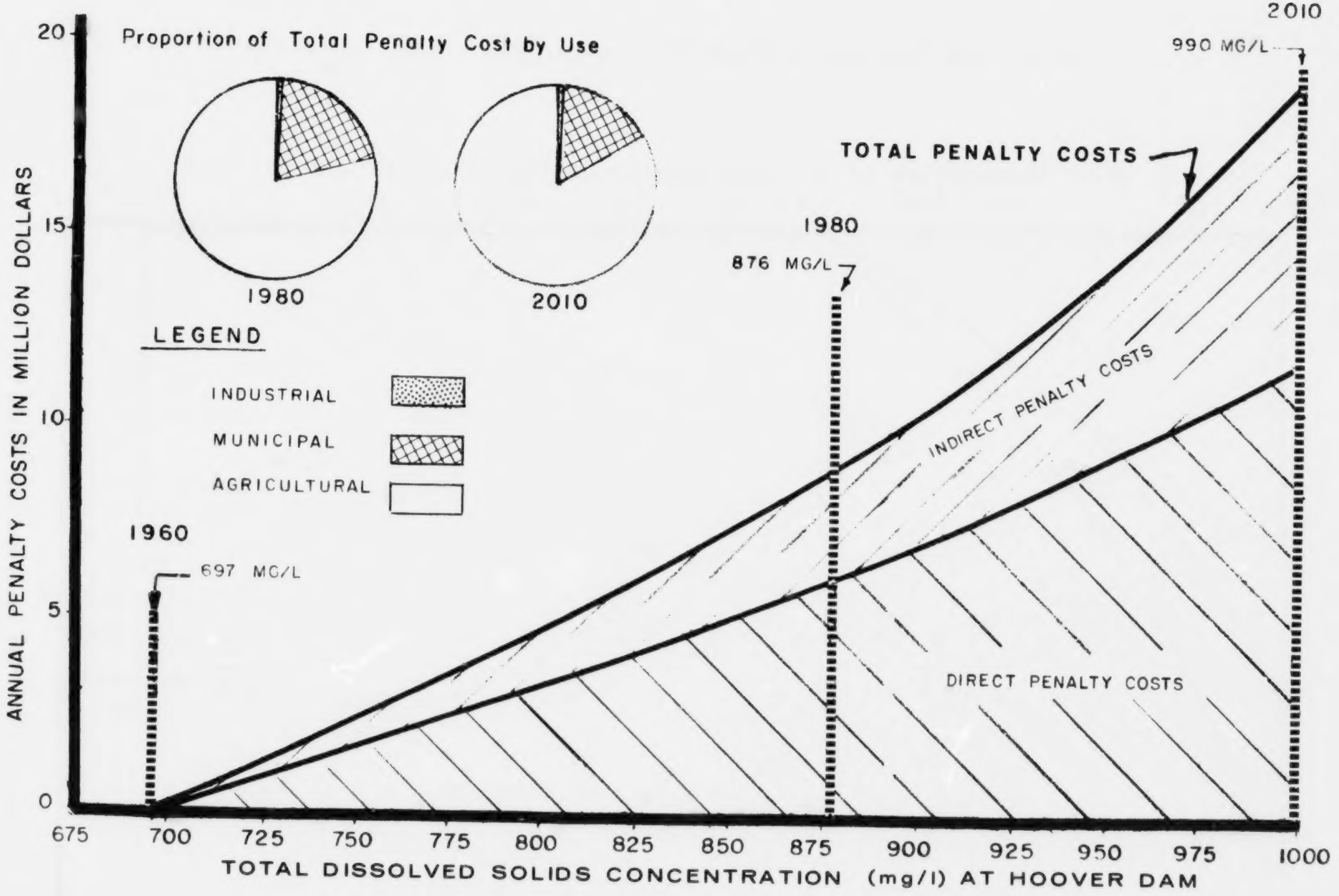

Figure 22. Total Penalty Costs Incurred in the Southern California Study Area

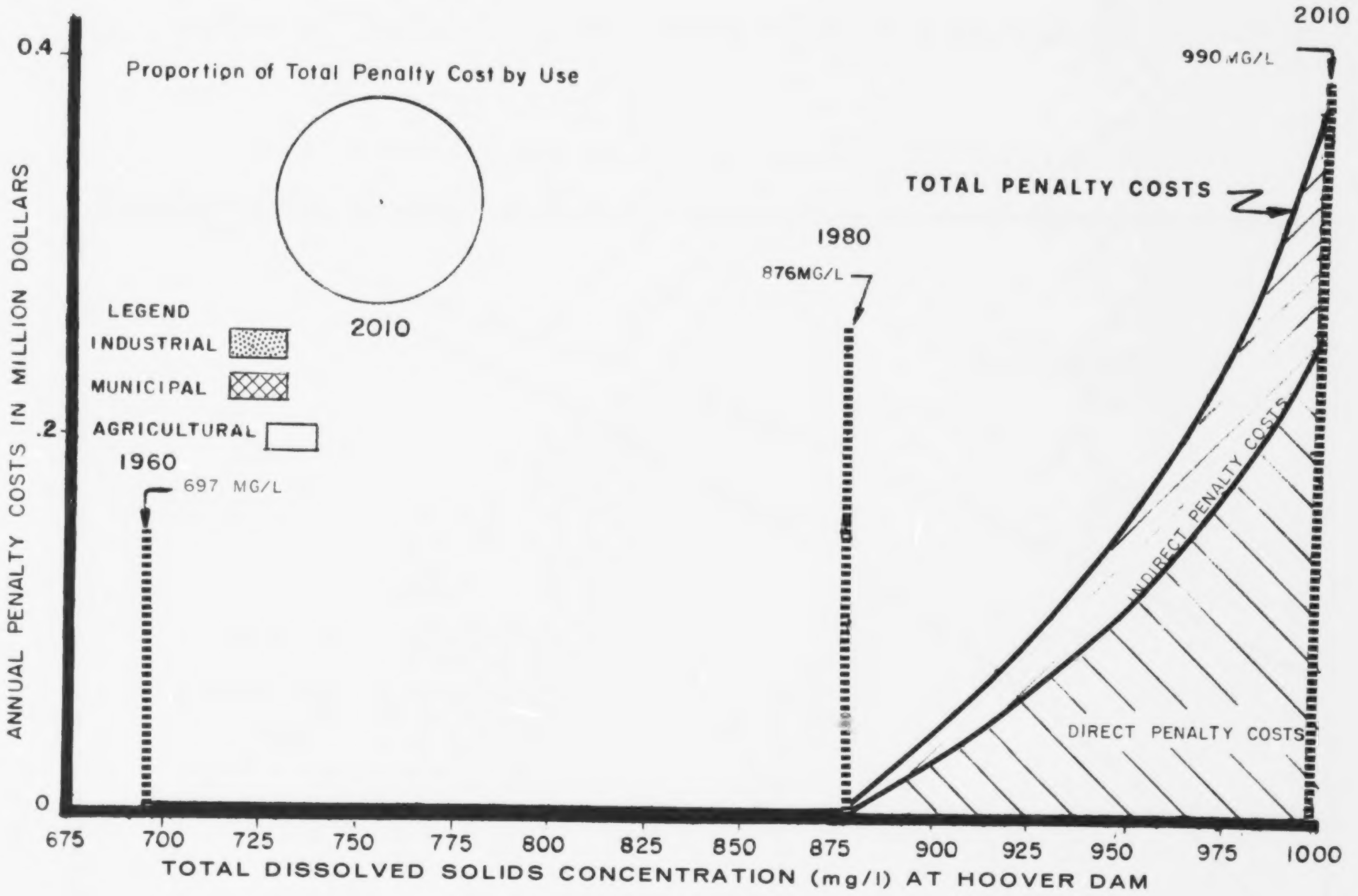

Figure 23. Total Penalty Costs Incurred in the Gila Study Area

was assumed to occur in target year 2010 because the Upper Basin allotment is not projected to be fully utilized until that time.

For purposes of this analysis minimum compact delivery was taken as 8.25 MAF per year, based on the assumption that the Upper Basin must deliver 7.5 MAF to the Lower Basin and 0.75 MAF to Mexico. To satisfy Mexico's total apportionment of 1.50 MAF, the Lower Basin must, in turn, deliver 0.75 MAF of their allotted share. A comparison of 2010 water budgets for the Lower Basin for both the projected study condition and the minimum compact delivery condition is shown in Table 40. Allocation of the supply for the Lower Basin under the minimum compact condition is shown in Table 41. This supply condition was incorporated into the flow and salt load routing model, and a new array of mineral qualities was developed as shown in Table 42.

The new array of mineral qualities was incorporated into the model and new total penalty costs were determined. The results show that the model is relatively sensitive to flow. Total penalty costs to all users of Colorado River water below Hoover Dam as shown in Table 43 increased from $25.4 million to $27.8 million annually, or about ten percent, because of an assumed reduction in the available water supply of four percent. A comparison of the results based upon the two different flow conditions is shown in Figure 24.

SURFACE EQUATION OF DIRECT ECONOMIC IMPACTS

Figure 25, a display of three traces on a three-dimensional figure called a response surface, illustrates total direct user costs as a function of water quality at Hoover Dam. The curves represent total user costs associated with each of the three target years, 1960, 1980

Table 40. Lower Basin Water Budgets for Year 2010 Under Projected and Minimum Compact Conditions

	Projected Supply Condition (maf)	Minimum Compact Supply Condition (maf)
Delivery at Lees Ferry, Arizona	8.629	8.250
Inflows and Water Salvage	1.323	1.323
Reservoir Evaporation & Other Depletions	-1.250	-1.250
Available for Use in Lower Basin	8.702	8.323

Table 41 Assumed Allocation of Colorado River Water Among Lower Basin States & Mexico Under Minimum Compact Conditions

State or Republic	Allocation (maf)
California	4.400
Arizona	2.023[a]
Nevada	0.300
Mexico	1.600[b]
Total	8.323

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[a] A volume constraint was applied to the Central Arizona Project decreasing the diversion volume from [illegible]00,000 acre-feet/year to 373,000 acre-feet/year.

[b] Includes 0.100 maf of uncontrolled and unmeasurable underflows.

Table 42. Mineral Quality for Year 2010 Under Projected and Minimum Compact Conditions

Station	Projected Conditions		Minimum Compact Delivery	
	TDS (mg/l)	Hardness (mg/l)	TDS (mg/l)	Hardness (mg/l)
Colorado River at Hoover Dam	990	460	1,022	470
Colorado River at Parker Dam	985	460	1,018	470
Colorado River at Palo Verde	1,082	495	1,115	505
Colorado River at Imperial Dam	1,223	540	1,256	550

Table 43. Total Penalty Costs for Projected Conditions and Minimum Compact Conditions for Year 2010
($1,000 annually)

Type of Penalty Costs	Lower Main Stem Study Area		Southern California Study Area		Gila Study Area		Total	
	Projected	Min.[a] Compact	Projected	Min.[a] Compact	Projected	Min.[b] Compact	Projected	Min. Compact
Agricultural								
Direct	2,423.0	2,672.3	10,072.1	10,934.0	245.7	82.3	12,740.8	13,688.6
Indirect	2,237.2	2,292.8	6,194.5	7,271.1	125.4	42.2	8,557.1	9,606.1
Total	4,660.2	4,965.1	16,266.6	18,205.1	371.1	124.5	21,297.9	23,294.7
Industrial								
Direct	410.2	469.3	102.6	115.0			512.8	584.3
Indirect	14.5	44.5	5.5	9.2			20.0	53.7
Total	424.7	513.8	108.1	124.2			532.8	638.0
Municipal								
Direct	779.0	841.0	2,239.0	2,416.0			3,018.0	3,257.0
Indirect	39.3	42.0	506.7	535.6			546.0	577.6
Total	818.3	883.0	2,745.7	2,951.6			3,564.0	3,834.6
Total Direct	3,612.2	3,982.6	12,413.7	13,465.0	245.7	82.3	16,271.6	17,529.9
Total Indirect	2,291.0	2,379.3	6,706.7	7,815.9	125.4	42.2	9,123.1	10,237.4
TOTAL	5,903.2	6,361.9	19,120.4	21,280.9	371.1	124.5	25,394.7	27,767.3

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a/ Quantity Unconstrained.
b/ Quantity Constrained.

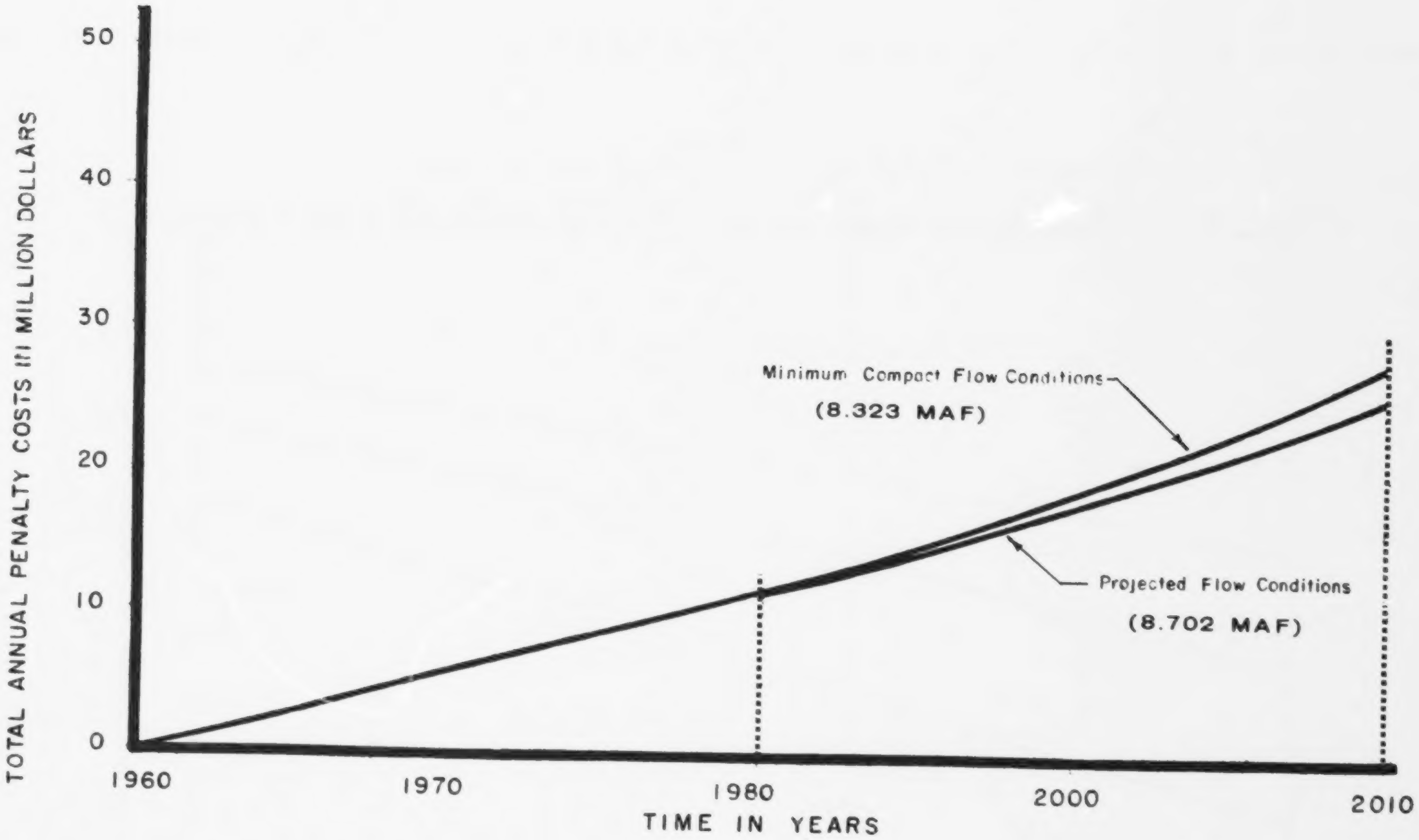

Figure 24.Comparision of Total Penalty Costs for Projected & Minimum Compact Water Supply Conditions

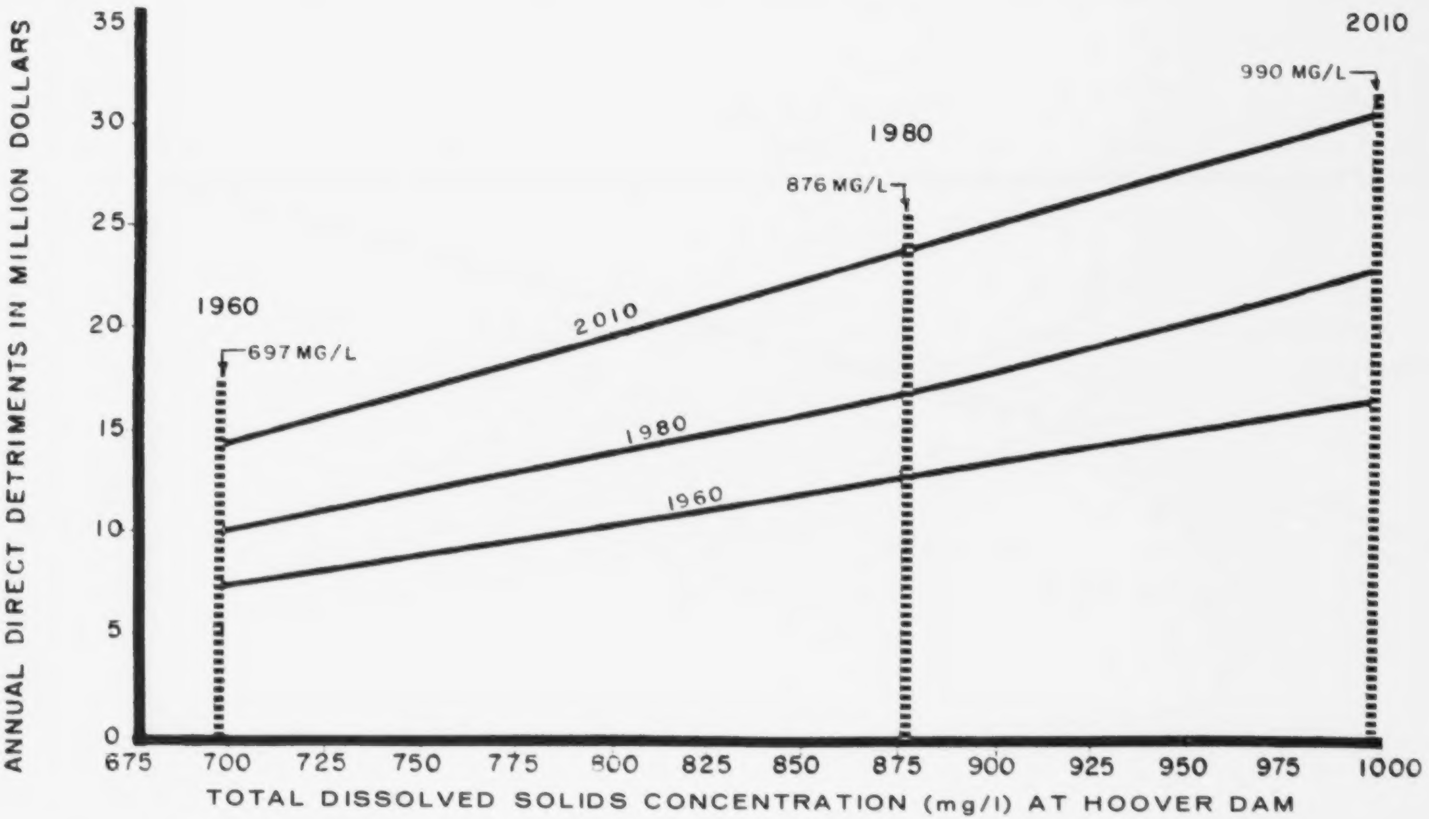

Figure 25. Summary of Direct Salinity Detriments to All Colorado River Water Users Below Hoover Dam

and 2010 The three traces on this surface were selected arbitrarily for illustration purposes. To be more general, an equation was developed that defined the response surface. With the equation, user costs for water qualities and economies at any time in the future can be investigated without duplicating all the detailed analysis described in Chapters III and IV.

The response surface equation is a polynomial in the form:

$$S = Ax^2 + Bxy + Cy^2 + Dx + Ey$$

where S = Annual direct detriments in million dollars below Hoover Dam (1960 dollars);

x = The total dissolved solids concentration (mg/l) at Hoover Dam;

y = The economic year, where 1950 = 0, 1980 = 20, and 2010 = 50; and

A, B, C, D, and E are the coefficients of the polynomial as determined by the least squares technique.

The coefficients are:

$A = 0.22663 \times 10^{-4}$

$BB = 0.45845 \times 10^{-3}$

$C = -0.19157 \times 10^{-3}$

$D = -0.50383 \times 10^{-2}$

$E = -0.17265 \times 10^{0}$

The response surface equation can be used to evaluate the economic benefits which would be realized if the mineral quality at Hoover Dam could be improved. Assuming that means are available to reduce the projected 1975 mineral quality at Hoover Dam from 840 mg/l to 740 mg/l, benefits could be calculated as follows:

For the Projected conditions; $x = 840$, $y = 15$. Thus,

$$S = .22663 \times 10^{-4}(840)^2 + .45845 \times 10^{-3}(840)\ (15) + (-.19157 \times 10^{-3})\ (15)^2 + (-.50803 \times 10^{-2})\ (840) + (-.17265)\ (15)$$

$S = 14.8$ million dollars annually.

For the proposed condition, $x = 740$ and $y = 15$.

Thus

$$S = .22663 \times 10^{-4}(740)^2 + .45845 \times 10^{-3}(740)\ (15) + (-.19157 \times 10^{-3})\ (15)^2 + (-.50803 \times 10^{-2})\ (740) + (-.17265)\ (15)$$

$S = 11.1$ million dollars annually.

The net worth or negative penalty cost to the economies is then,

Worth = 14.8 - 11.1 = 3.7 or $3,700,000 annually.

The indirect benefits which would accrue to water users would be calculated by input-output analysis.

CHAPTER VI. CONCLUSIONS

Projected degradation of mineral quality in the Colorado River during the next four decades will impose significant economic penalties upon water users in the Lower Basin and Southern California areas. These penalty costs will be incurred generally by consumptive users of water. Little or no detrimental effects are anticipated for non-consumptive uses of water such as recreation, water sports, native fauna, navigation, hydropower generation, and esthetic enjoyment.

Adverse effects of salinity are anticipated in municipal, industrial, and irrigated agriculture water uses. Among these three, irrigated agriculture is by far the most important in terms of amount of water used. Even after considering the heavy urban demand of the Los Angeles - San Diego metropolitan areas, irrigation still accounts for 85 to 90 percent of all water presently consumed in the Colorado River system.

Based upon projected patterns of future water resource and economic development, mineral quality was forecasted at key locations in the Basin for the target years 1980 and 2010. The mineral qualities at Hoover Dam and Imperial Dam are projected as 876 mg/l and 1,056 mg/l, respectively in 1980 and 990 mg/l and 1,223 mg/l, respectively in 2010. These quality levels represent increases in salinity concentrations over 1960 levels of 179 mg/l (25.7 percent) and 297 mg/l (39.1 percent) at Hoover Dam and Imperial Dam, respectively, for the year 1980. These concentrations are projected to undergo additional increases by the year 2010 of 114 mg/l (13.0 percent) and 167 mg/l (15.8 percent) at the same locations, respectively.

Nearly all economic penalty costs will be incurred by water users in the Lower Colorado River Basin and Southern California Water Service area. Direct economic losses to water users in these areas will amount to 7.5 million dollars annually by the year 1980. The magnitude of these damages which represent the direct added costs of using a degraded water supply, will increase to 16.3 million dollars annually by the year 2010.

Indirect economic effects caused by the direct impact upon water users will represent an additional loss to the regional economy of 9.1 million dollars annually by the year 2010. Of the total (direct and indirect) annual economic impact in 2010 (25.4 million) nearly 84 percent will be incurred as a result of the direct impact upon irrigated agriculture water users.

BIBLIOGRAPHY

APPENDIX B

1. U. S. Department of Health, Education and Welfare, Public Health Service, "Drinking Water Standards, 1962," U. S. Government Printing Office, Washington, D. C., 1962.
2. State of California, "Water Quality Criteria," Second Edition, State Water Quality Control Board, Sacramento, California, 1963.
3. Sawyer, Clair N., "Chemistry for Sanitary Engineers," McGraw-Hill Book Company, New York, 1960
4. U. S. Department of Commerce, Business and Defense Services Administration, August 20, 1964. Colorado River Project file correspondence, Region VIII, U. S. Public Health Service, Denver, Colorado.
5. State of California, Department of Water Resources, Sacramento, California, "Water Use by Manufacturing Industries in California, 1957-1959," Bulletin No. 124, April 1964
6. Nordel, Eskel, "Water Treatment for Industrial and Other Uses," Second Edition, Reinhold Publishing Corporation, New York, 1961.
7. Betz Laboratories, Inc., "Betz Handbook of Industrial Water Conditioning," Betz Laboratories, Inc., Philadelphia, Pa., 1962.
8. American Water Works Association, New York, "Water Quality and Treatment," Second Edition, 1951.
9. Anonymous, "Progress Report of Committee on Quality Tolerances of Water for Industrial Uses," Journal New England Water Works Association, Volume 54, 1940.
10. U. S. Department of Agriculture, U. S. Salinity Laboratory, "Saline and Alkali Soils," Agriculture Handbook No. 60, 1954
11. U. S. Department of Health, Education and Welfare, Public Health Service, "Proceedings of the National Conference on Water Pollution, December 12-14, 1960," U. S. Government Printing Office, Washington, D. C., 1961.
12. Eaton, F. M., "Deficiency, Toxicity and Accumulation of Boron in Plants," Journal Agricultural Research, Volume 69, Illustration 1944.
13. Eaton, F. M., "Significance of Carbonates in Irrigation Waters," Soil Science, Volume 69, 1950.

14. Federal Water Pollution Control Administration, U. S. Department of the Interior, "Water Quality Criteria," Report of the National Technical Advisory Committee to the Secretary of the Interior, April 1, 1968.

15. Ellis, M. M., "Detection and Measurement of Stream Pollution," U. S. Fish and Wildlife Service Bulletin No. 22, 1936.

16. State of California, "The Ecology of the Salton Sea, California, in Relation to the Sport-Fishery," Department of Fish and Game, Sacramento, California, 1961.

17. State of California, Santa Ana Regional Water Pollution Control Board, Santa Ana, California, Resolutions 54-4, January 28, 1955, and 57-7, May 24, 1957.

18. State of California, "The California Water Plan," Department of Water Resources, Sacramento, California, Bulletin No 3, May, 1957.

19. State of California, "Investigation of Alternative Aqueduct Systems to Serve Southern California," Appendix B, Bulletin No. 78, Department of Water Resources, Sacramento, California, January, 1959

20. U. S. Department of the Interior, "Quality of Water, Colorado River Basin," January, 1965.

21. Bureau of Reclamation, U. S. Department of the Interior, "Pacific Southwest Water Plan," August, 1963.

22. Geological Survey, U. S. Department of the Interior, "Surface Water Records of Arizona," 1961.

23. U. S. Department of the Interior, "Supplemental Information Report on the Central Arizona Project," January, 1964.

24. Eldridge, Edward F., "Return Irrigation Water - Characteristics and Effects," U. S. Department of Health, Education and Welfare, Public Health Service, Region IX, Portland, Oregon, May 1, 1960.

25. Garnsey, *et al*, "Past and Probable Future Variations in Stream Flow in the Upper Colorado River - Part I," Bureau of Economic Research, University of Colorado, Boulder, Colorado, October, 1961.

26. Tipton and Kalmbach, Inc., Upper Colorado River Commission, "Water Supplies of the Colorado River - Part I," July, 1965

27. Iorns, W. V., Hembree, C. H., and Oakland, G. L., "1965 Water Resources of the Upper Colorado River Basin - Technical Reports," U. S Geological Survey Professional Papers 441 and 442.

28. U. S. Department of the Interior, "Quality of Water, Colorado River Basin," Progress Report No. 4, January, 1969.

29. U. S. Department of the Interior, "Quality of Water, Colorado River Basin," Progress Report No. 3, January, 1967.

30. Hill, Raymond A., "Leaching Requirements in Irrigation," Reprint from Journal of the Irrigation and Drainage Division, American Society of Civil Engineers, March, 1961.

31. Soil and Water Conservation Research Division, "Salt Tolerance of Plants," Agricultural Research Service, U. S. Department of Agriculture, December, 1964.

32. Bureau of the Census, U. S. Department of Commerce, "Statistical Abstract of the United States," 1964.

33. Bureau of the Census, U. S. Department of Commerce, "Industrial Water Use, 1958 Census of Manufacturers," U. S. Government Printing Office, 1961.

34. State of California, "Water Use by Manufacturing Industries in California, 1957-1959," Bulletin 124, Department of Water Resources, Sacramento, California, April, 1964.

35. State of Nevada, Department of Health and Welfare, unpublished report on survey of industrial water uses, August, 1964.

36. American Boiler and Affiliated Industries Manufacturers' Association, "Limits for Boiler Water Concentrations in Units with a Steam Drum."

37. Howson, L. R., "Economics of Water Softening," Journal of the American Water Works Association, February, 1962

38. Leasure, J. William, "Population Projections for the Three Lower Subbasins of the Colorado River Basin," San Diego State College, San Diego, California, June, 1964.

39. Anonymous, "Statistics on Population of Households," Journal of the American Water Works Association, 42:904, September, 1950.

40. U. S. Bureau of the Census, "Census of Manufacturers: 1963 Water Use in Manufacturing," Subject Report MC63(1)-10, Washington, D.C.: U. S. Government Printing Office, 1966.

41. Select Committee on National Water Resources, U. S. Senate, Water Supply and Demand, Committee Print No. 32, 1960.

42. Study by the National Aluminate Corporation reported in the State of California, Department of Water Resources, Sacramento, California, "Investigation of Alternative Aqueduct Systems to Serve Southern California," Appendix B, Part Five.

43. University of Arizona, "The Quality of Arizona Irrigation Water," Report 223, September, 1964.

44. University of Arizona, "Quality of Arizona Domestic Waters," Report 217, November, 1963.

45. Miernyk, William H., "The Element of Input-Output Analyses," New York Random House, 1965, Library of Congress No. 65-23339.

46. University of Colorado, "An Interindustry Analysis of the Colorado River Basin in 1960 with Projections to 1980 and 2010," Edited by Bernard Udis, Associate Professor of Economics, Boulder, Colorado, June, 1968.

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